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Non-Line-of-Sight Cannon (NLOS-C) System Crew Shock Loading, Evaluation of Potential Head and Neck Injury

by Michael E. LaFiandra and Harry Zywiol

ARL-TR-4228 **August 2007**

NOTICES

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Michael E. LaFiandra
Human Research and Engineering Directorate, ARL

Harry Zywiol
U.S. Army Tank-Automotive Research, Development, and Engineering Center

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14. ABSTRACT

The Future Combat Systems (FCS) non-line of sight cannon (NLOS-C) is an artillery weapon that will use a 155-mm cannon that can fire as far as 35 km and will be capable of automatically firing and reloading ammunition, as many as six rounds per minute. The goal of this project was to quantify the effects of weapon fire recoil on a surrogate human occupant of the NLOS-C. In March and April 2004, the Tank-Automotive Research, Development, and Engineering Center (TARDEC) ride motion simulator (RMS) was used to simulate the effects of gun firing shock on a Hybrid III instrumented anthropometric test device (ATD) capable of measuring head acceleration, neck force and torque. The RMS simulated firing scenarios that ranged from 0 to 15 degrees of azimuth and 0 to 30 degrees of elevation and included two different harness types (3 point or 5 point) and two seat heights (normal and raised 3 inches). The raw data for this project were collected by TARDEC's Motion Base Technologies Team and their contractors. The data were sent to the U.S. Army Research Laboratory's (ARL) Human Research Engineering Directorate for analysis. Biomechanics researchers at ARL were tasked with relating the neck force and torque and head accelerations to established injury criteria for the neck and head. Data from the Hybrid III ATD were compared to the standards established by the National Highway Traffic Safety Administration (NHTSA). Based on the standards used by NHTSA, the acceleration of the head and the forces and torques experienced by the neck of the occupant of an NLOS-C during weapon firing are less than the injury criteria for the 50th percentile male. Resulting probability of injury rates were nearly zero for head injuries but were as high as about 0.147 (14.7%) for moderate neck injuries and as high as 0.029 (2.9%) for critical neck injuries. The established injury criteria do not account for possible cumulative effects of the repeated impulses of weapon firing (as many as six rounds per minute), so the actual probability for neck injury may be greater than reported here. At the time this report was written, a standard for multiple impulse events had not been established.

15. SUBJECT TERMS

biomechanics; FCS; future combat system; head and neck injury

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Acknowledgments

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Executive Summary

The Future Combat Systems non-line-of-sight cannon (NLOS-C) is an artillery weapon that will employ a 155-mm cannon that can fire as far as 35 kilometers and will be capable of automatically firing and reloading ammunition (as many as 10 rounds per minute). The goal of this project was to quantify the effects of weapon fire recoil on a surrogate human occupant of the NLOS-C. In March and April 2004, the U.S. Army Tank-Automotive Research, Development, and Engineering Center's (TARDEC's) ride motion simulator (RMS) was used to simulate the effects of gun firing shock on anthropometric test devices (ATDs).

A Hybrid III instrumented ATD capable of measuring head acceleration, neck force, and neck torque was placed in the seat of the RMS, and data were recorded from the ATD during the firing scenarios. The motion of the RMS during the firing scenarios was controlled, based on data recorded from a Dynamic Analysis Design System Simulation, provided to TARDEC by General Dynamics Land Systems. Firing scenarios ranged from 0 to 15 degrees of azimuth and 0 to 30 degrees of elevation and included two different harness types (3 point or 5 point) and two seat heights (normal and raised 3 inches). The raw data for this project were collected by TARDEC's Motion Base Technologies Team and its contractors. The data were sent to the U.S. Army Research Laboratory's (ARL's) Human Research and Engineering Directorate for analysis, relative to quantifying potential neck and head injury. Biomechanics researchers at ARL were tasked with relating the neck force and torque and head accelerations measured by the Hybrid III instrumented ATD to established injury criteria for the neck and head. State-of-the-art modeling is inadequate because sufficiently validated models do not currently exist that have the required resolution to obtain the forces and torques needed for this analysis. Therefore, an instrumented ATD was used for data collection instead of our relying solely on computer modeling of impulse and head movement. Data from the Hybrid III ATD were compared to the standards established by the National Highway Traffic Safety Association (NHTSA).

Specifically, the potential for neck injury was estimated, based on the N_{ij}, and the potential for head injury was estimated, based on NHTSA's head injury criteria (HIC). The "ij" refers to indices for four injury mechanisms, namely, tension and extension, tension and flexion, compression and extension, compression and flexion (Kleinberger, Sun, Eppinger, Kuppa, & Saul, 1998). The N_{ij} is a measure of the axial and shear loads imposed on the neck, as well as the bending moments. The HIC is essentially the integral of accelerations over a given time period. In 1986, the appropriate time period was determined to be 36 ms, which resulted in the HIC_{36}; however, in 2000, NHTSA proposed a change in the time period to 15 ms, which resulted in HIC_{15}.

Based on the standards used by the NHTSA, head acceleration and the forces and torques experienced by the neck of an occupant of an NLOS-C during weapon firing are less than the injury criteria for the 50th percentile male. Resulting probability of injury rates were nearly zero for head injuries but were as high as about 0.147 for moderate neck injuries and as high as 0.029 for critical neck injuries. This indicates that 14.7% of the time the weapon is fired, a moderate neck injury can be expected and that 2.9% of the time the weapon is fired, a critical neck injury is expected. These results could be interpreted that a moderate neck injury could be expected once every seven shots, and a critical neck injury would be expected once every two or three shots. The estimated probability of neck injury does not account for possible cumulative effects of the repeated impulses of the weapon firing (as many as 10 rounds per minute), so the actual probability for neck injury may be greater than reported here. For instance, in a repeated impulse situation, each impulse may result in a micro-trauma to the neck structure or neck muscle fatigue that is below the threshold of what would be considered injurious. However, the micro-trauma may weaken the structure of the neck (or fatigue the neck muscles), resulting in an increased probability of injury in subsequent firings.

A major limitation to this work is that the applied injury criteria and probability for injury calculations are designed for single-impulse events instead of multiple impulse events (such as the repeated firing of the weapon). Because of this and the fact that there may be a cumulative effect of repeated impulses on the probability of injury, the injury probabilities reported may be artificially low. Although previous researchers have identified this as a limitation in their work (Hundley, 1987) and noted the need to establish human tolerance criteria for lower level impact accelerations, an exhaustive literature review did not uncover a standard for multiple events similar to what may be experienced by the occupants of the NLOS-C. This is a substantial limitation in the knowledge base that needs to be addressed through basic and applied research.

1. Project Background

The Future Combat Systems (FCS) non-line-of-sight cannon (NLOS-C) is an artillery weapon equipped with a 155-mm cannon that can fire as far as 35 kilometers. The FCS NLOS-C will weigh only 19 tons, which is relatively light for an artillery weapon. Consequently, the acceleration of the vehicle resulting from the impulse imparted during weapon firing is greater than that of current vehicles (which have much greater mass). Additionally, the NLOS-C will be capable of automatically firing and reloading ammunition (as many as 10 rounds per minute). The goal of this project was to quantify the effects of weapon fire recoil on a simulated human occupant of the NLOS-C.

The U.S. Army Tank-Automotive Research, Development, and Engineering Center's (TARDEC's) ride motion simulator (RMS) was used to simulate the effects of gun firing shock on test anthropometric test devices (ATD). The RMS is situated at the U.S. Army Tank-Automotive and Armaments Command (TACOM) in Warren, Michigan, and is a reconfigurable six-degree-of-freedom (6-DOF) hexapod motion simulator. It has a dynamic range of movement, is "man" rated (meaning live humans can serve as participants within the limitations of the RMS protocol) and is designed to simulate a wide variety of ground vehicles' motions and movements over various terrains and conditions. In this test, the RMS was used to simulate the dynamic motion of the NLOS-C driver during weapon firing scenarios.

A Hybrid III instrumented ATD capable of measuring neck force and torque and head acceleration was placed in the seat of the RMS and data were recorded from the ATD during the firing scenarios. The raw data for this project were collected by TARDEC's Motion Base Technologies Team and their contractors. The data were sent to the U.S. Army Research Laboratory's (ARL's) Human Research and Engineering Directorate for analysis relative to quantifying potential neck and head injury. Biomechanics researchers at ARL were tasked with relating the neck force and torque and head accelerations measured by the Hybrid III instrumented ATD to established injury criteria for the neck and head. Data from the Hybrid III ATD were compared to the standards established by the National Highway Traffic Safety Association (NHTSA).

Specifically, the potential for neck injury was estimated, based on the N_{ij}, and the potential for head injury was estimated, based on NHTSA's head injury criteria (HIC) (Eppinger, Sun, Bandak, Haffner, Khaewpong, & Maltese, 1999; Kleinberger, Sun, Eppinger, Kupper, & Saul, 1998; Eppinger, Sun, Kuppa, & Saul, 2000). The N_{ij} is a measure of the axial and shear loads imposed on the neck, as well as the bending moments. The "ij" refers to indices for four injury mechanisms, namely, tension and extension (TE), tension and flexion (TF), compression and extension (CE), compression and flexion (CF) (Kleinberger et al., 1998).

The HIC was first proposed by Versace (1971), but NHTSA modified the measure to be more appropriate for the duration of exposures typical for human tests. HIC is essentially the integral of accelerations over a given time period. In 1986, the appropriate time period was determined to be 36 ms, resulting in the HIC_{36} (Kleinberger et al., 1998). However, in 2000, NHTSA proposed a change in the time period to 15 ms, resulting in HIC_{15} (Eppinger et al., 2000). The change from a 36-ms to a 15-ms window occurred because available human tests at the time demonstrated that the probability of injury from longer duration events was low. However, because both the duration and magnitude of the events that are be experienced by occupants of the NLOS-C during weapon firing may be potentially injurious, both the HIC_{15} and the HIC_{36} for each condition are documented in this report.

An alternate standard to apply may be the International Standardization Organization (ISO): 2631-5 (ISO, 2004). However, applying this standard to the current data set would not be appropriate for several reasons. First, ISO 2631-5 was written for conditions such as vehicles traveling over rough surfaces, small boats in rough seas, mechanical hammers, etc., in which there is a longer duration exposure to whole-body vibration. The NLOS-C will be stationary when firing. Therefore, it was concluded by biomechanics researchers at ARL that weapon firing will result in more intermittent impulses than those to which ISO 2631-5 is designed to be applied. ISO 2531-5 is designed to determine potential for injury to the lumbar area of the spine, based on the average daily exposure to whole-body vibration and is focused on average daily exposures and predicting life-time exposure. ISO 2631-5 would be more appropriate for investigating the effects of NLOS-C movement over rough terrain (e.g., movement to an objective rally point or similar) than the effects of weapon firing.

The limitation of using NHTSA standards is that they are for a single impulse event (such as a car accident), whereas the occupants of the NLOS-C will likely be exposed to multiple impulse events (such as the repeated firing of the cannon). Although previous researchers have identified this as a limitation in their work (Hundley, 1987) and noted the need to establish human tolerance criteria for lower level impact accelerations, an exhaustive literature review did not uncover a standard for multiple events similar to what may be experienced by the occupants of the NLOS-C. A standard is needed for multiple impulse events over various time frames, possibly a standard that incorporates parts of ISO2631-5 and the NHTSA standards.

2. Objectives

The objective of this study was to quantify the effect of turret azimuth and elevation, seat height, and occupant restraint type during weapon firing of an NLOS-C on occupant N_{ij}, Hic_{15}, and Hic_{36}.

3. Equipment

3.1 Ride Motion Simulator (RMS)

The RMS is a reconfigurable 6-DOF hexapod simulator that has a dynamic range of movement. It is man rated and can hold a single occupant. The RMS is designed to simulate ground vehicles. Typically, the RMS is used to support human-in-the-loop experiments. However, the high gun fire shocks simulated in this experiment (>2g's) exceeded the current human-rating protocols for the RMS, which require the use of ATDs for this study. Before testing, the RMS was tuned by TARDEC's Motion Base Technologies Team for optimum performance, which ensures the simulator will react as realistically as possible.

To simulate the interior of the FSC common crew cab, which is used in the NLOS-C, aluminum brackets were mounted in the RMS cab (see figure 1). These brackets replicated the interior of the FCS common crew cab and included potential impact points for the head, arms, and legs. These brackets were designed and mounted, based on computer-aided design drawings of the actual design provided by the United Defense Limited Partnership and General Dynamics Land Systems (GDLS) (Oldaugh, Zywiol, & Stork, 2004). For this study, the most notable bracket is called the cupola. The cupola is an aluminum bracket around the head that allowed for 3 inches of head movement.

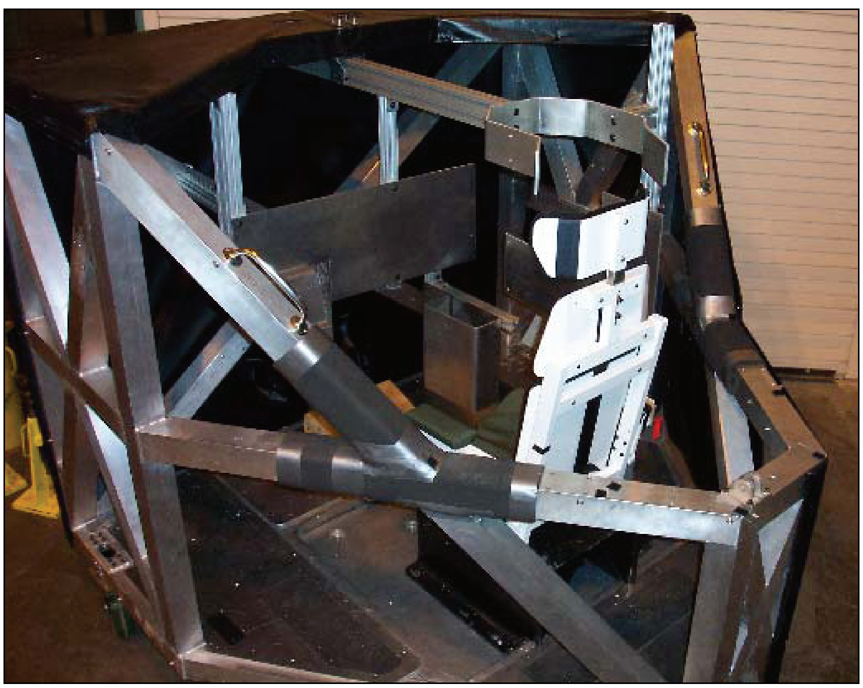

Figure 1. Interior of the RMS, including the aluminum brackets simulating the potential impact points for the head (including the cupola), arms, and legs.

The RMS was set up to simulate stationary vehicle firing. The 6-DOF motions used to simulate weapon firing of the MCS were recorded from a Dynamic Analysis Design System (DADS) simulation, provided by GDLS. In-house software at TARDEC was used to convert the output from the DADS simulation into a form that could be used to control the RMS. The seat was mounted to the floor during the simulated firings. More information about this is given in Oldaugh et al. (2004).

3.2 Hybrid III Anthropometric Test Device (ATD)

One of TARDEC's support contractors, Dynamic Research, Inc. (DRI), develops, manufactures, maintains, and provides rental of specialized crash test dummies for various applications, including injury evaluation and protection system feasibility research. The DRI crash dummies are unique among commercially available motor vehicle crash test dummies in that all data acquisition components, including sensors and power sources, are internal. This is especially important in applications where instrument cables could interfere with or distort dummy motions (as in, for example, unbelted car occupants, pedestrians, motorcyclists, all-terrain vehicles, etc.). In this regard, it is well suited to the study of multiple impacts (Oldaugh et al., 2004).

The specific ATD used for this study was a Hybrid III, 50th percentile male ATD. The ATD weighed 172.3 pounds, was 69 inches tall, and had a sitting height of 34.8 inches (NHTSA, 2007). While referred to as the 50th percentile male, this ATD would be characterized as between the 50th and 55th percentile for weight, 50th percentile for standing height, and 20th percentile for sitting height according to the 1988 U.S. Army Anthropometric Survey (ANSUR) database (Gordon, Churchill, Clauser, Bradtmiller, McConville, Tebbets, & Walker, 1989).

The ATD is instrumented with force transducers and accelerometers capable of providing information about the forces exerted on and acceleration of the head, neck, thorax, and limbs. Specifically for this study, acceleration of the head (all three orthogonal directions) and force and torque about the upper neck are of interest.

4. Experimental Design

4.1 Independent Variables

There were two levels of weapon firing (Zone 4 and Zone 5) that simulated two firing distances of the NLOS-C. Zone 4 represents a shorter firing distance than Zone 5. For all conditions, increasing azimuth represents a clockwise rotation of the turret. For Zone 4, the test was not a full factorial design relative to azimuth and elevation. Conditions were

- Condition 1: azimuth = 0; elevation = 30
- Condition 2: azimuth = 15; elevation = 0

- Condition 3: azimuth = 15; elevation =15
- Harness type (3-point versus 5-point harness)
- Seat height (normal height versus raised 3 inches)

For Zone 5, the test was a full factorial design relative to azimuth and elevation:

- Azimuth conditions (0 and 15 degrees)
- Elevation conditions (0, 15 and 30 degrees)
- Harness type (3-point and 5-point)
- Seat height (normal height versus raised 3 inches)

4.2 Dependent Variables

- Head injury criteria, with a 15-ms window (Hic_{15}). See the data analysis for more information about the time windows.
- Head injury criteria with a 36-ms window (HIC_{36}),
- Neck injury criteria (N_{ij}).

4.3 Statistical Analysis

4.3.1 Zone 4 Analysis

A repeated measures analysis of variance (ANOVA) with within-subject effects of condition and harness type was used to determine if statistically significant differences existed between conditions and harness types and to determine if a significant Condition x Harness interaction was present. Analyses were performed within seat height conditions; no between-seat height analyses were performed.

4.3.2 Zone 5 Analysis

A repeated measures ANOVA with within-subject effects of azimuth, elevation, and harness type was used to determine if statistically significant differences existed between azimuth conditions, elevation conditions, and harness type conditions and to determine if a significant Azimuth x Elevation interaction was present within a harness type. Three-way interactions were not investigated. Analyses were performed within seat height conditions; no between-seat height analyses were performed.

The Statistical Package for the Social Sciences (SPSS)[1] version 14.0.1 was used for all statistical analyses.

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[1]SPSS is a registered trademark of SPSS, Inc.

5. Procedure

The experimental procedure consisted of a series of repetitive steps. These steps were repeated for each azimuth, elevation, harness type, and seat height condition. This procedure was followed:

1. Set RMS input to simulate specific azimuth and elevation condition.
2. Set the ATD to a seated default position for seat = normal height (0 height) condition. The ATD was strapped into the 3-point or 5-point harness in the same manner a human occupant would be strapped in if the human used all the provided straps correctly.
3. Bring the RMS to ride level.
4. Begin recording with the ATD data acquisition system.
5. Begin recording simulator response.
6. Run a shock pulse through the RMS.
7. Stop recording all data acquisition systems.
8. Stop the test briefly to reset the ATD position if needed. The ATD needed to be repositioned if it was no longer in the original default position.
9. Repeat steps 2 through 9 until three trials of data were collected for a given azimuth, elevation, and harness type condition.
10. Download data from ATD.
11. Repeat steps 1 through 11 for each azimuth, elevation, and harness condition.
12. Repeat steps 1 through 12 for seat = 3 inch higher condition.

Data were sampled from the ATD at 10,000 Hz and were filtered with a 6th order low pass Butterworth filter at 2500 Hz. The data ARL received had already been filtered and scaled appropriately and were in the units of *g* (gravity) for acceleration, *Nm* (newton-meters) for the torques, and *kN* (kilonewtons) for force.

6. Data Analysis

Data were analyzed with custom written MATLAB[2] (version 7.1.0) programs.

6.1 N_{ij} Calculation

N_{ij} was calculated according to NHTSA guidelines (Kleinberger et al., 1998; Eppinger et al., 1999; Eppinger et al., 2000). Equation 1 was used to calculate N_{ij}.

$$N_{ij} = \frac{F_z}{F_{\text{int}}} + \frac{M_y}{M_{\text{int}}} \tag{1}$$

in which F_z is the axial load, F_{int} is the critical intercept value of load used for normalization, M_y is the flexion/extension moment, and M_{int} is the critical intercept value for the moment used for normalization. F_z and M_y are recorded from the ATD. F_{int} and M_{int} are pre-determined values specific to the size ATD used for the study. Because this study used a Hybrid III 50th percentile male ATD, F_{int} was set to 3600 N for tension and compression, and M_{int} was set to 410 Nm for flexion and 125 Nm for extension (Kleinberger et al., 1998; Eppinger et al., 1999; Eppinger et al., 2000).

The maximum of the absolute value of the N_{ij} (equation 2) was calculated and is reported.

$$N_{ij} = \max(abs(N_{ij})) \tag{2}$$

NHTSA recommends an injury criterion for N_{ij} of 1.0, meaning test results of greater than 1.0 pose a significant injury risk, while test results of less than 1.0 are considered acceptable for a single impulse event. In addition to the injury criteria, the N_{ij} can be used to calculate the probability of several different types of injuries. Table 1 summarizes the equation used to estimate the potential for each injury relative to the Abbreviated Injury Scale (AIS) (Eppinger et al., 1999). The AIS is an injury scale ranging from 0 (no injury) to 6 (not survivable) (Association for the Advancement of Automotive Medicine, 2005).

[2]MATLAB is a registered trademark of The MathWorks.

Table 1. Equations used to calculate probability of injury, based on N_{ij}.

Abbreviated Injury Scale	Severity of Injury	Equation
2	Moderate or greater	$p = \frac{1}{1+e^{2.054-1.195N_{ij}}}$
3	Serious or greater	$p = \frac{1}{1+e^{3.227-1.969N_{ij}}}$
4	Severe or greater	$p = \frac{1}{1+e^{2.693-1.195N_{ij}}}$
5	Critical or greater	$p = \frac{1}{1+e^{3.817-1.195N_{ij}}}$

6.2 HIC Calculation

HIC was calculated according to NHTSA guidelines with two different time windows: 15 ms and 36 ms. These time windows were chosen because they are recommended by NHTSA (Kleinberger et al., 1998; Eppinger et al., 1999; Eppinger et al., 2000). HIC was calculated by equation 3:

$$HIC = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) \qquad (3)$$

in which t_1 and t_2 represent any two points in time (determined by the time window) during the acceleration impulse, and $a(t)$ represents the resultant acceleration of the head at a specific point in time (units for acceleration are *g*). Therefore, to calculate HIC_{15}, t_2 - t_1 was set to 0.015 second and to calculate HIC_{36}, t_2 - t_1 was set to 0.036 second; *dt* was 0.0001 for all analyses. The units for time are seconds.

NHTSA recommends injury criteria of 700 for Hic_{15} and 1000 for Hic_{36}. These criteria indicate that test results of greater than 700 for Hic_{15} or 1000 for Hic_{36} pose a significant injury risk, while test results of less than the criteria are considered acceptable. In addition to the injury criteria, the Hic can be used to calculate the probability of moderate head injuries via equation 4.

$$p = N\left(\frac{\ln(HIC) - \mu}{\sigma}\right) \qquad (4)$$

in which N represents the cumulative normal distribution, μ = 6.96352, and σ = 0.84664 (Eppinger et al., 1999).

7. Results

7.1 Zone 4, Seat Height Normal

There was a significant main effect of condition ($F = 11.596$, $p = 0.002$) and harness type ($F = 134.159$, $p = 0.000$) and a significant Condition x Harness Type interaction ($F = 7.284$, $p = 0.008$) on Hic_{15} when the seat was at the normal height (table 2). Similarly, there was a significant main effect of condition ($F = 33.603$, $p = 0.000$) and harness type ($F = 132.252$, $p = 0.000$) and a significant Condition x Harness Type interaction ($F = 19.144$, $p = 0.000$) on Hic_{36} when the seat was at the normal height. Additionally, there was a significant main effect of condition ($F = 12.59$, $p = 0.001$) and harness type ($F = 187.328$, $p = 0.000$) and a significant Condition x Harness Type interaction ($F = 6.381$, $p = 0.013$) on N_{ij} when the seat was at the normal height.

Table 2. F-ratios and *p*-values for zone 4, seat height = normal.

Effect of	**Hic_{15}**	**Hic_{36}**	**N_{ij}**
Condition (p-Value)	0.002	0.000	0.001
Condition (F-Ratio)	11.596	33.603	12.59
Harness (p-value)	0.000	0.000	0.000
Harness (F-Ratio)	134.159	132.252	187.328
Condition * harness (p-Value)	0.008	0.000	0.013
Condition * harness (F-Ratio)	7.284	19.144	6.381

Pairwise comparisons were performed to determine which conditions were statistically different from each other (table 3). Statistically significant differences were determined between the conditions 1 and 2 and between conditions 2 and 3 for HIC_{15} and HIC_{36}. Additionally, statistically significant differences were determined between conditions 1 and 3 and between 2 and 3 for N_{ij}. Pairwise comparisons were not performed to determine which harness types were different because there were only two levels of harness type.

Table 3. *p*-values for pairwise comparisons: zone 4, seat height = normal.

p-values from pairwise comparisons: zone 4, seat height normal				
Conditions		**Hic_{15}**	**Hic_{36}**	**N_{ij}**
1	2	0.000	0.000	0.225
1	3	0.062	0.100	0.004
2	3	0.018	0.000	0.000

Means (and standard error of the mean) for each azimuth and elevation condition for Hic_{15} are summarized in table 4 and shown in figure 2.

Table 4. Means (SEM) for NLOS-C zone 4, seat position normal: Hic_{15}.

		Condition		
		Az=0; El = 30	Az=15, El=0	Az=15, El=15
Harness	3 pt.	1.219 (0.056)	1.143 (0.025)	1.141 (0.107)
	5 pt.	2.044 (0.061)	1.485 (0.051)	1.850 (0.069)

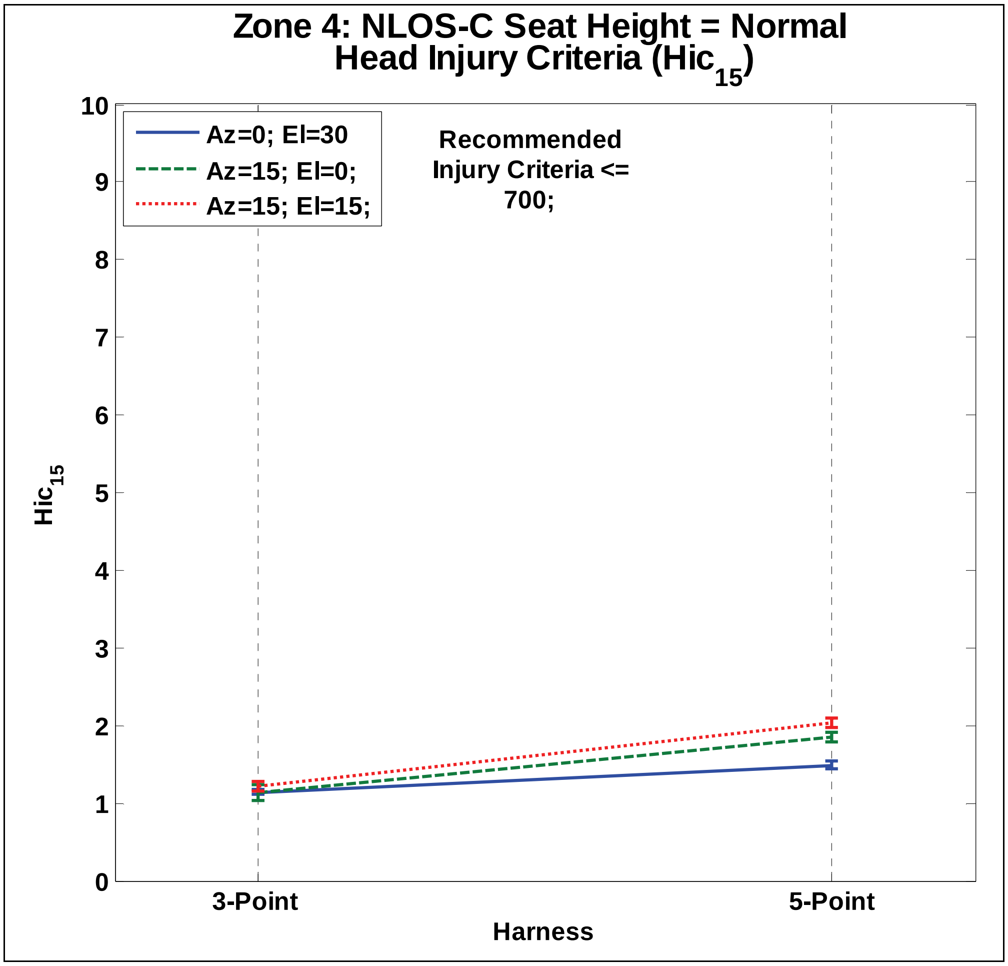

Figure 2. Zone 4: NLOS normal seat position Hic_{15} by condition.

Means (and standard error of the means) for each condition and harness type for Hic_{36} are summarized in table 5 and shown in figure 3.

Table 5. Means (SEM) for NLOS-C zone 4, seat position normal: Hic_{36}.

		Condition		
		Az=0; El = 30	Az=15, El=0	Az=15, El=15
Harness	3 pt.	2.300 (0.089)	2.113 (0.110)	2.388 (0.167)
	5 pt.	4.008 (0.083)	2.438 (0.038)	3.519 (0.140)

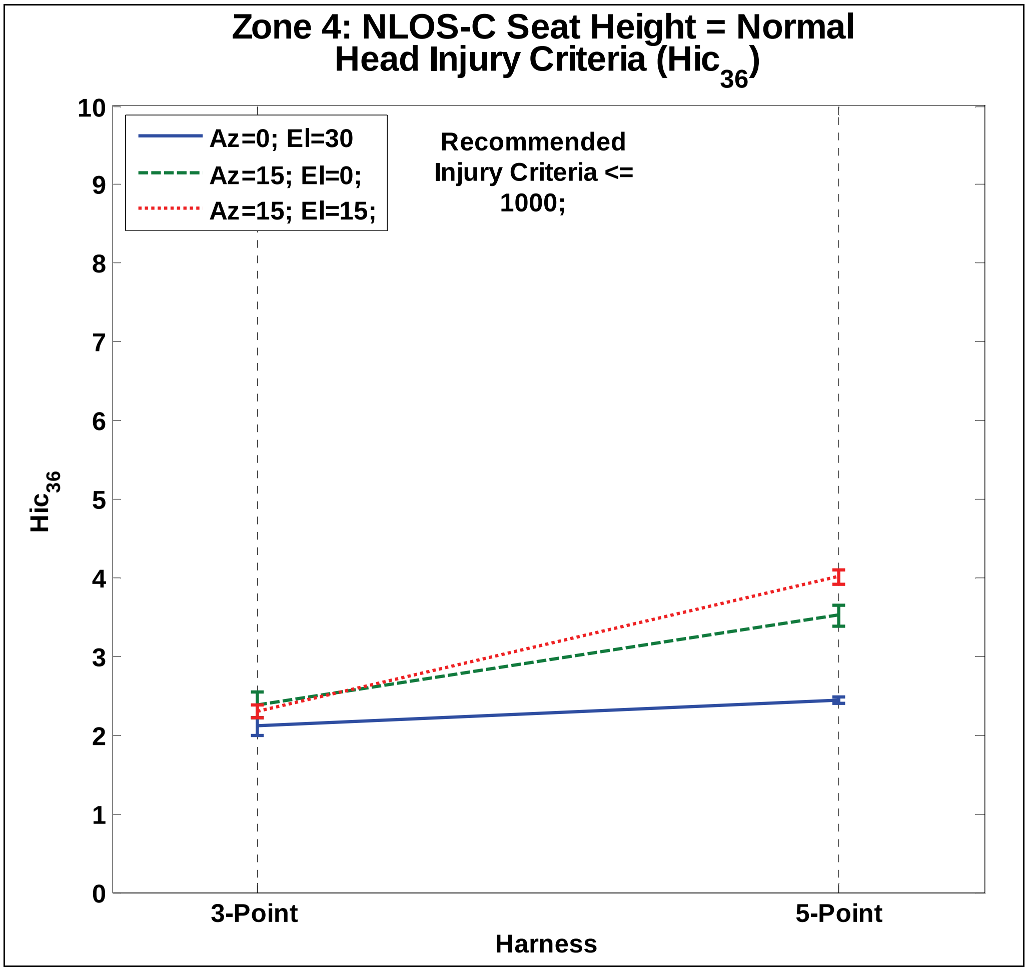

Figure 3. Zone 4 NLOS normal seat position Hic_{36} by condition.

Additionally, sample resultant head acceleration, Hic_{15} and Hic_{36} time series data from the azimuth = 15, elevation = 15, seat height = normal, 3-pt harness condition are presented in figure 4. Similar data for the azimuth = 15, elevation = 15, seat height = normal, 5-pt harness condition are presented in figure 5.

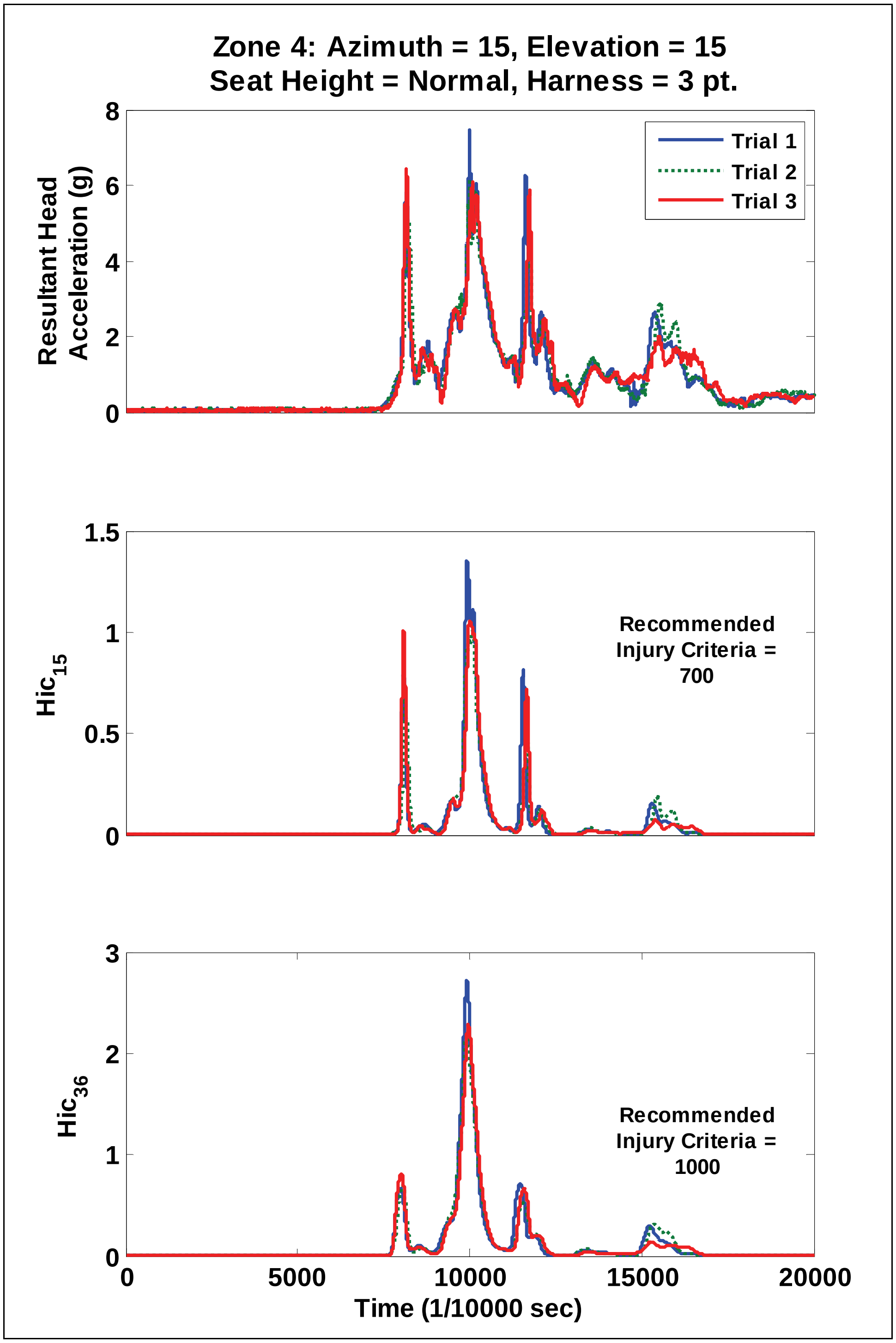

Figure 4. Sample time series data for the azimuth = 15 and elevation = 15, seat height = normal, 3-pt harness condition.

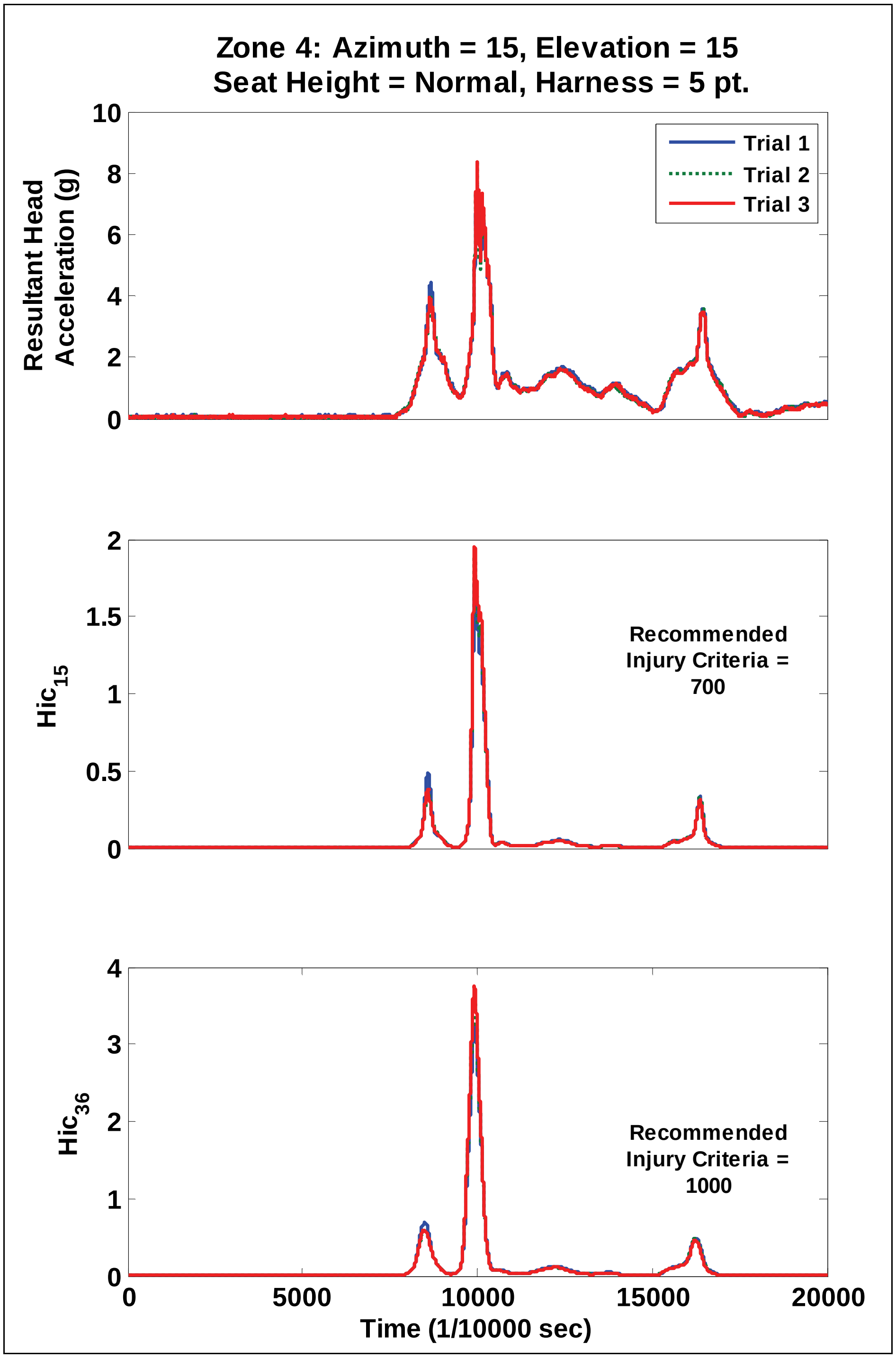

Figure 5. Sample time series data for the azimuth = 15 and elevation = 15, seat height = normal, 5-pt harness condition.

Means (and standard error of the means) for each condition and harness type for N_{ij} are summarized in table 6 and shown in figure 6.

Table 6. Means (SEM) for NLOS-C zone 4, seat position normal: N_{ij}.

		Condition		
		Az=0; El = 30	Az=15, El=0	Az=15, El=15
Harness	3 pt.	0.094 (0.002)	0.077 (0.004)	0.102 (0.004)
	5 pt.	0.123 (0.002)	0.131 (0.006)	0.141 (0.003)

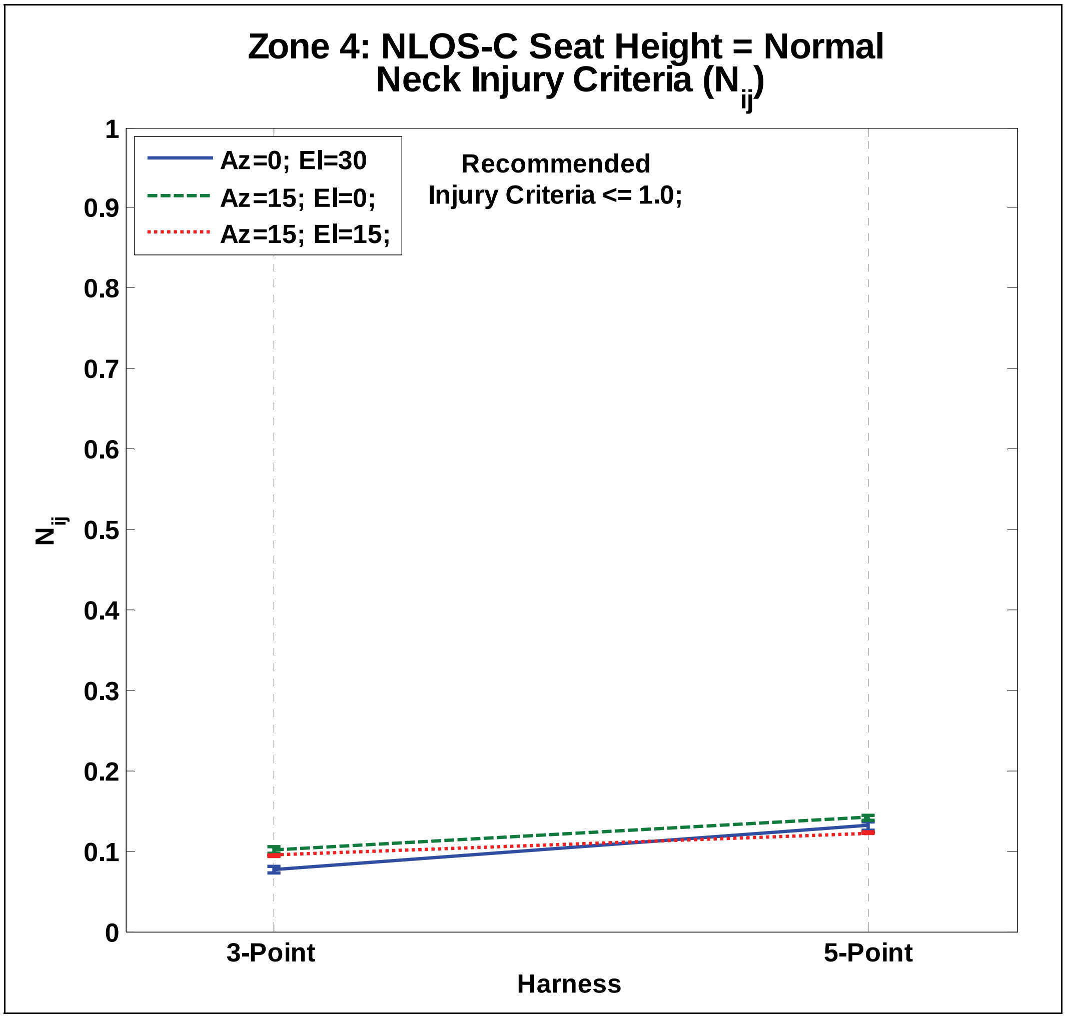

Figure 6. Zone 4 NLOS normal seat position N_{ij} by condition.

Sample time series data for the N_{ij} and the standard N_{ij} plot are presented for the azimuth = 15, elevation = 15, seat height = normal, 3-pt harness condition are presented in figure 7. Similar data for the azimuth = 15, elevation = 15, seat height = normal, 5-pt harness condition are presented in figure 8.

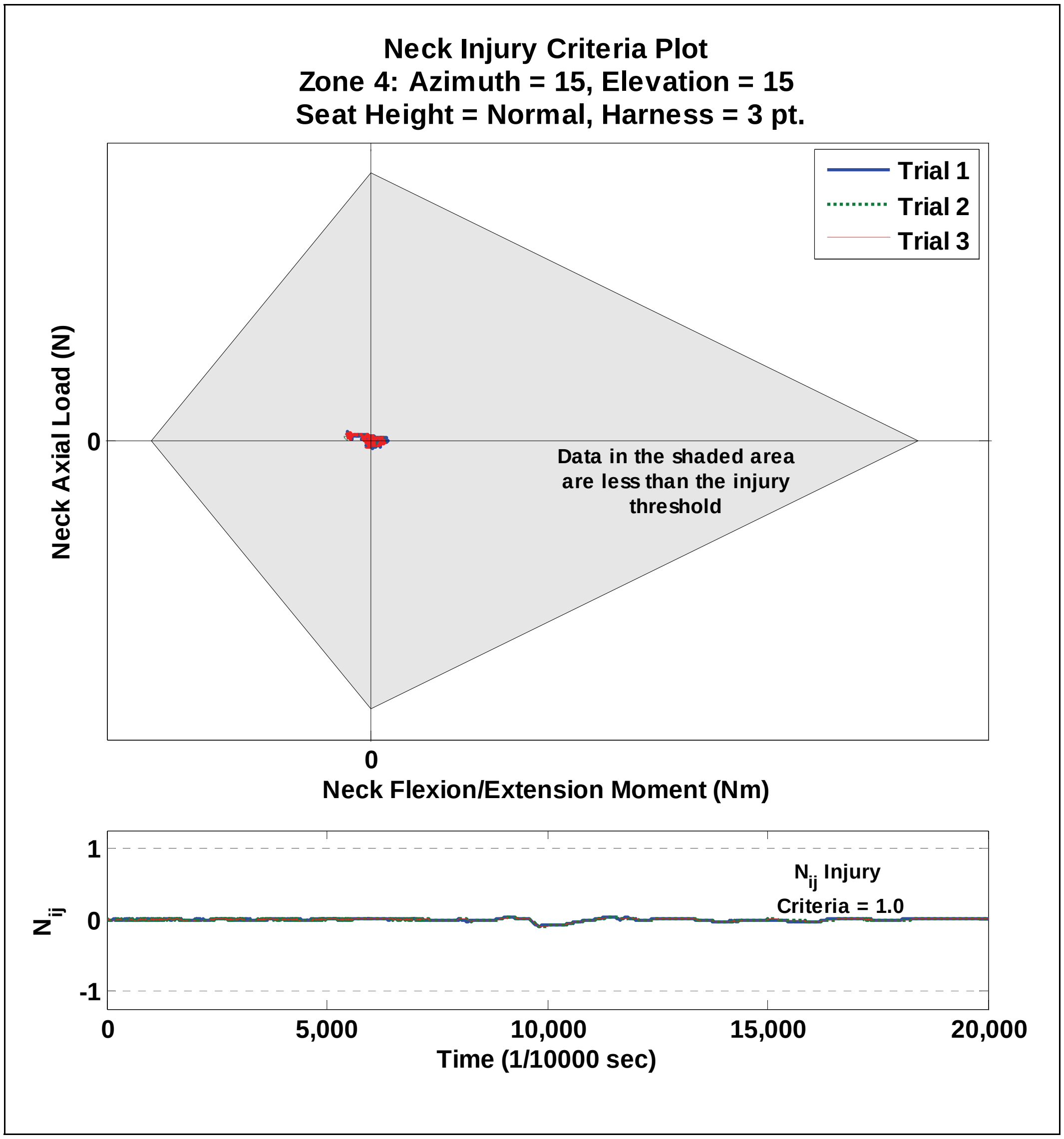

Figure 7. Sample N_{ij} time series data for the azimuth = 15 and elevation = 15, seat height = normal, 3-pt harness condition.

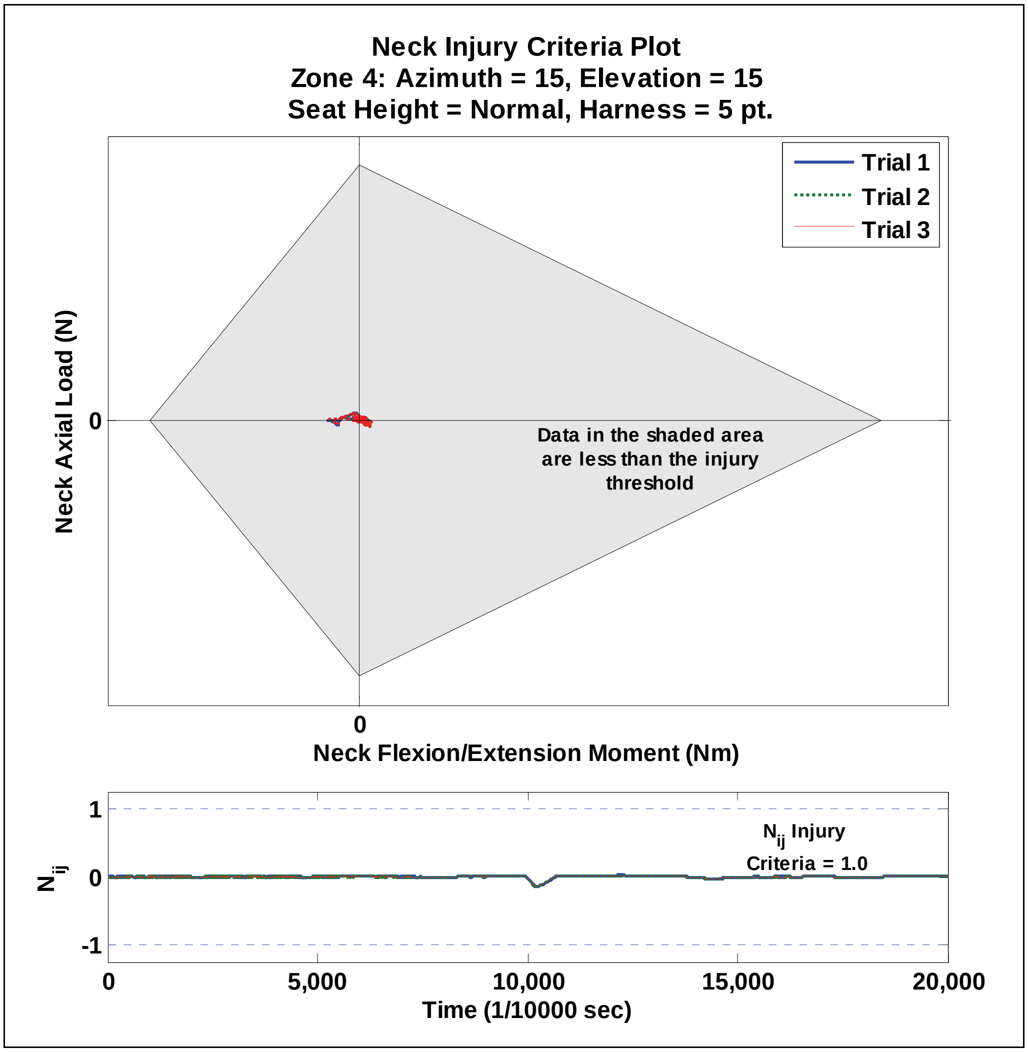

Figure 8. Sample N_{ij} time series data for the azimuth = 15 and elevation = 15, seat height = normal, 5-pt harness condition.

7.2 Zone 4, Seat Height Raised 3 inches

There was a significant main effect of condition (F = 4.196, *p* = 0.044) and harness type (F = 67.771, *p* = 0.000) and a significant Condition x Harness Type interaction (F = 5.600, *p* = 0.021) on Hic_{15} when the seat was in the + 3-inch-height condition (table 7). Similarly, there was a significant main effect of condition (F = 5.826, *p* = 0.019) and harness type (F = 80.801, *p* = 0.000) and a significant Condition x Harness Type interaction (F = 9.716, *p* = 0.004) on Hic_{36} when the seat was in the +3-inch-height condition. Additionally, there was a significant main effect of condition (F = 25.023, *p* = 0.000) and harness type (F = 42.618, *p* = 0.000) and a significant Condition x Harness Type interaction (F = 8.029, *p* = 0.007) on N_{ij} when the seat was in the +3-inch-height condition.

Table 7. F-ratios and *p*-values for statistics on zone 4, seat height = +3 inches

Effect of	**Hic_{15}**	**Hic_{36}**	**N_{ij}**
Condition (p-Value)	0.044	0.019	0.000
Condition (F-Ratio)	4.196	5.826	25.023
Harness (p-value)	0.000	0.000	0.000
Harness (F-Ratio)	67.771	80.801	42.618
Condition * harness (p-Value)	0.021	0.004	0.007
Condition * harness (F-Ratio)	5.600	9.716	8.029

Pairwise comparisons were performed on the N_{ij} data to determine which conditions where statistically different from each other (table 8). Statistically significant differences were observed between conditions 1 and 2 for HIC_{15} and HIC_{36}. Additionally, statistically significant differences were found between condition 1 and both conditions 2 and 3 for N_{ij}.

Table 8. *p*-values for pairwise comparisons: zone 4, seat height = + 3 inches.

p-values from pairwise comparisons: zone 4, seat height + 3 inches				
Conditions		**Hic_{15}**	**Hic_{36}**	**N_{ij}**
1	2	0.015	0.006	0.000
1	3	0.109	0.104	0.000
2	3	0.248	0.111	0.380

Means (and standard error of the mean) for each azimuth and elevation condition for Hic_{15} are summarized in table 9 and shown in figure 9.

Table 9. Means (SEM) for NLOS-C zone 4, seat position = +3 inches: Hic_{15}.

		Condition		
		Az=0; El = 30	Az=15, El=0	Az=15, El=15
Harness	3 pt.	6.886 (0.169)	4.927 (0.520)	5.283 (0.414)
	5 pt.	3.343 (0.156)	3.335 (0.134)	3.718 (0.277)

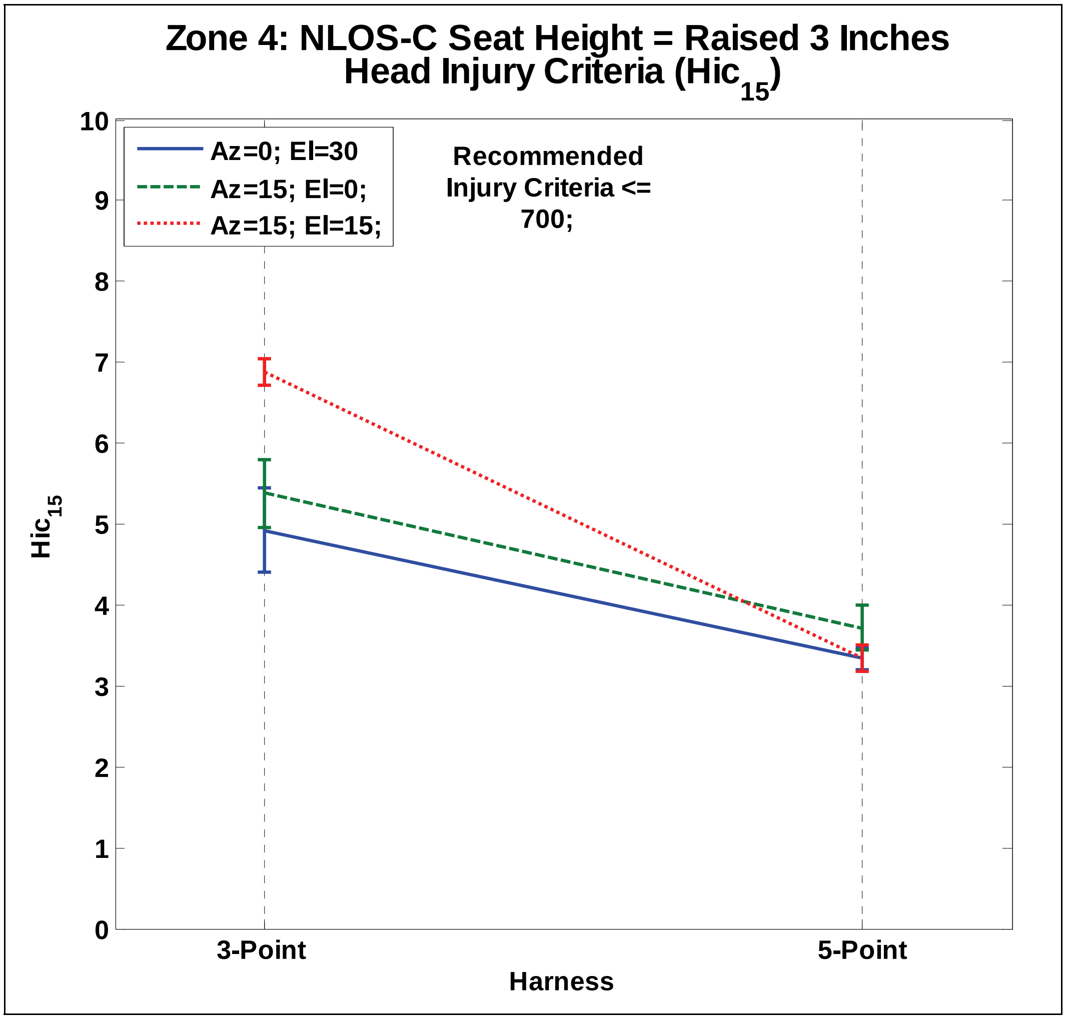

Figure 9. Zone 4: NLOS +3-inch seat position Hic_{15} by condition.

Means (and standard error of the means) for each condition and harness type for Hic_{36} are summarized in table 10 and shown in figure 10.

Table 10. Means (SEM) for NLOS-C zone 4, seat position = +3 inches: Hic_{36}.

		Condition		
		Az=0; El = 30	Az=15, El=0	Az=15, El=15
Harness	3 pt.	5.495 (0.139)	3.785 (0.233)	4.272 (0.387)
	5 pt.	2.639 (0.078)	2.740 (0.102)	3.072 (0.199)

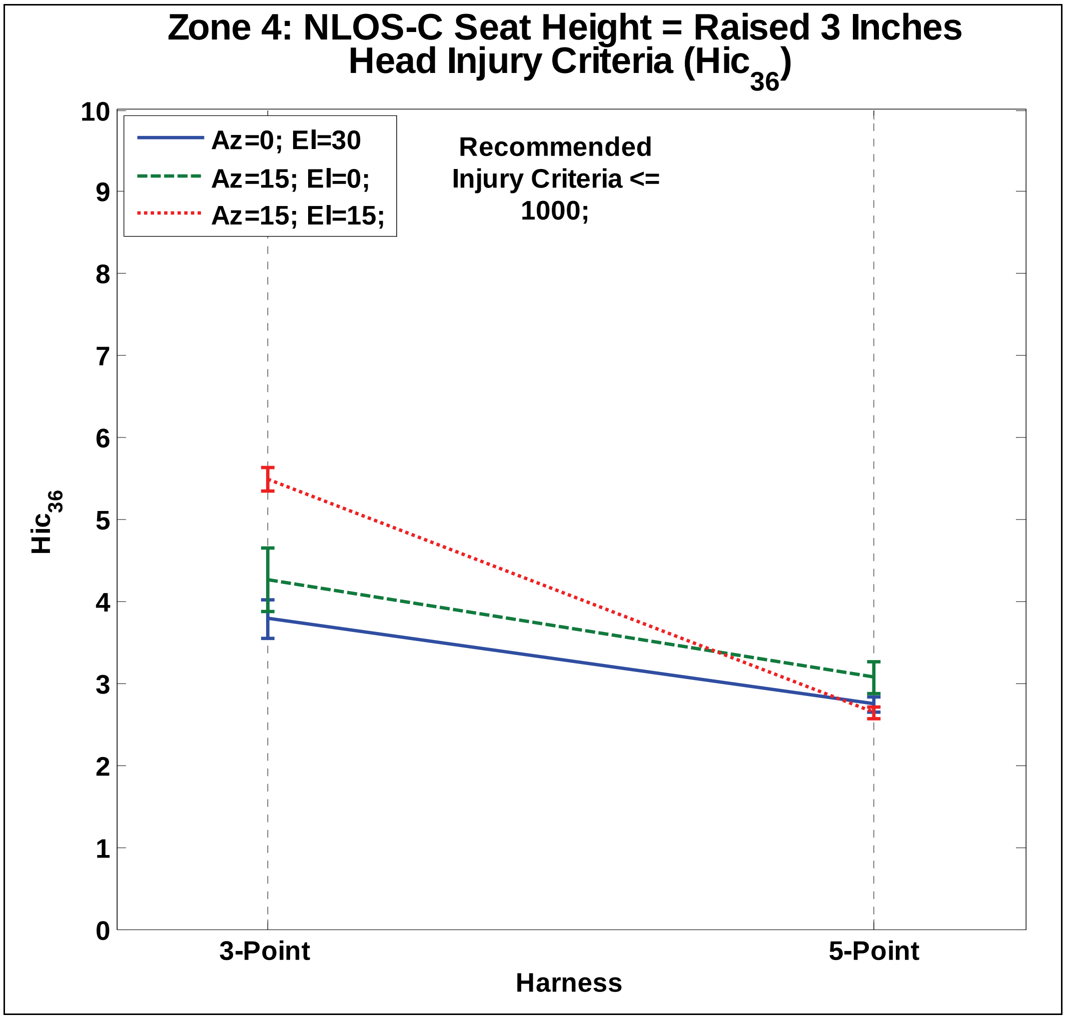

Figure 10. Zone 4 NLOS + 3-inch seat position Hic_{36} by condition.

Additionally, sample resultant head acceleration, Hic_{15} and Hic_{36} time series data from the azimuth = 15, elevation = 15, seat height = 3 inches, 3-pt harness condition are presented in figure 11. Similar data for the azimuth = 15, elevation = 15, seat height = + 3 inches, 5-pt harness condition are presented in figure 12.

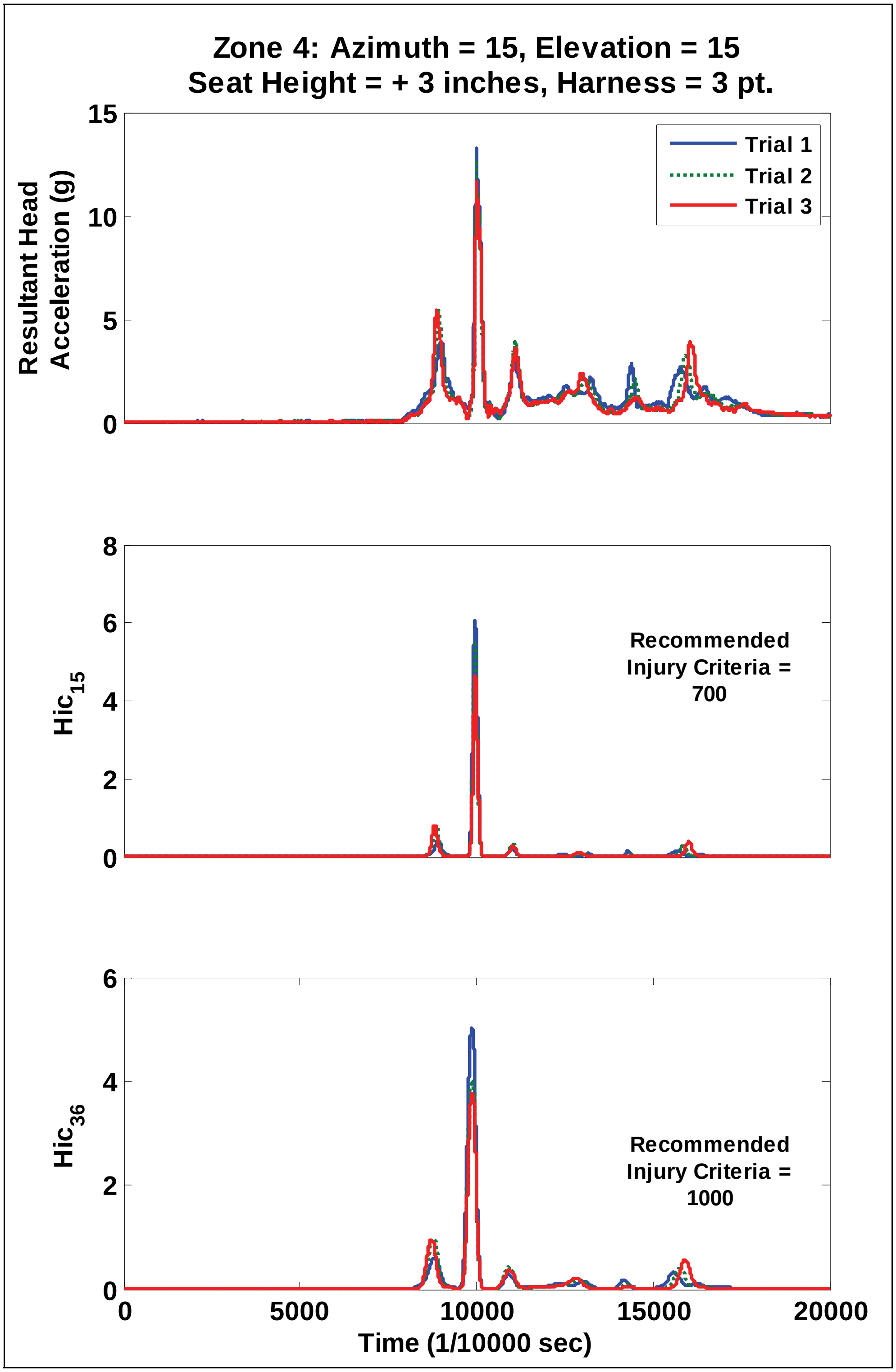

Figure 11. Sample time series data for the azimuth = 15 and elevation = 15, seat height = + 3 inches, 3-pt harness condition.

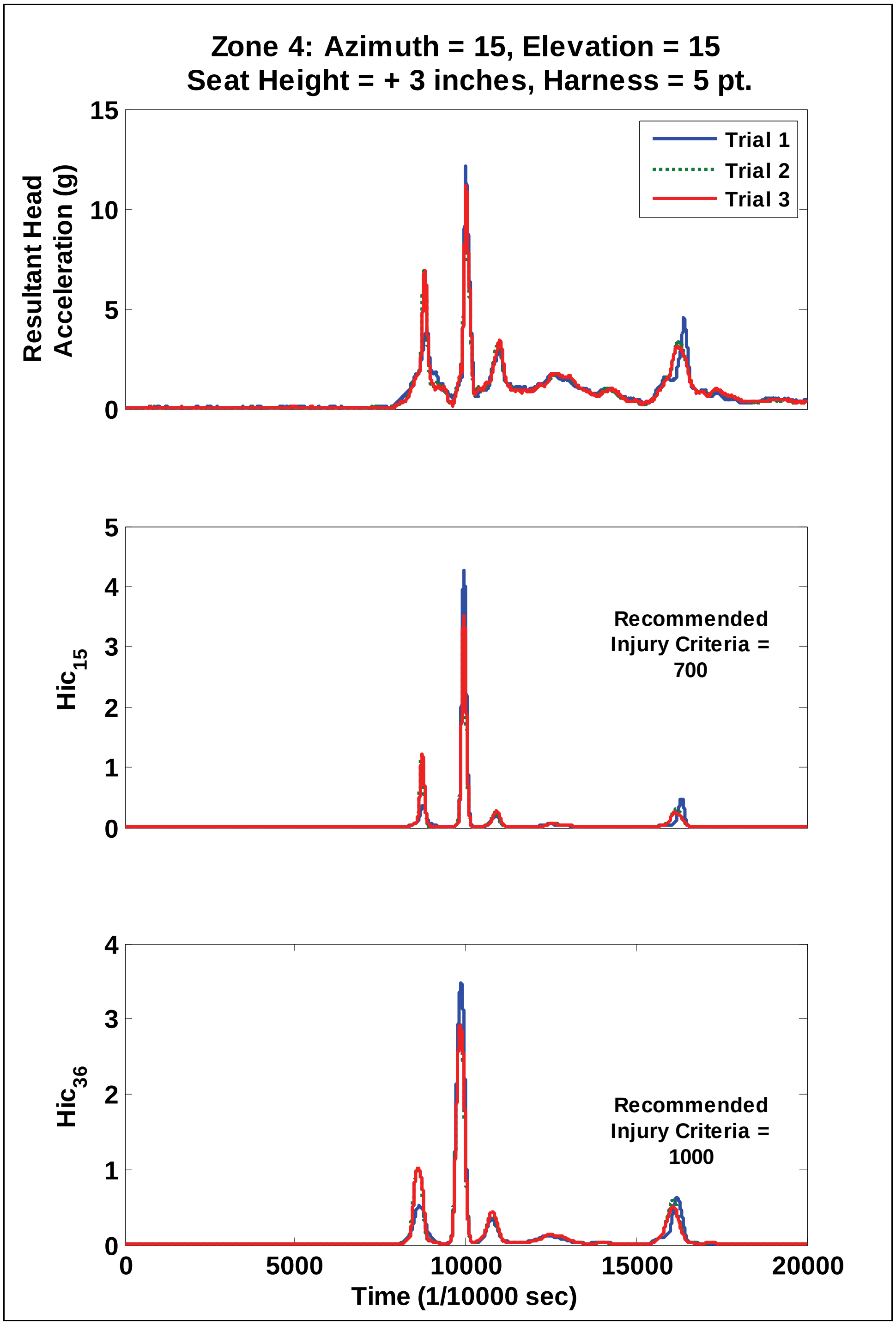

Figure 12. Sample time series data for the azimuth = 15 and elevation = 15, seat height = + 3 inches, 5-pt harness condition.

Means (and standard error of the means) for each condition and harness type for N_{ij} are summarized in table 11 and shown in figure 13.

Table 11. Means (SEM) for NLOS-C zone 4, seat position +3 inches: N_{ij}.

		Condition		
		Az=0; El = 30	Az=15, El=0	Az=15, El=15
Harness	3 pt.	0.066 (0.004)	0.042 (0.001)	0.045 (0.001)
	5 pt.	0.042 (0.004)	0.039 (0.001)	0.031 (0.002)

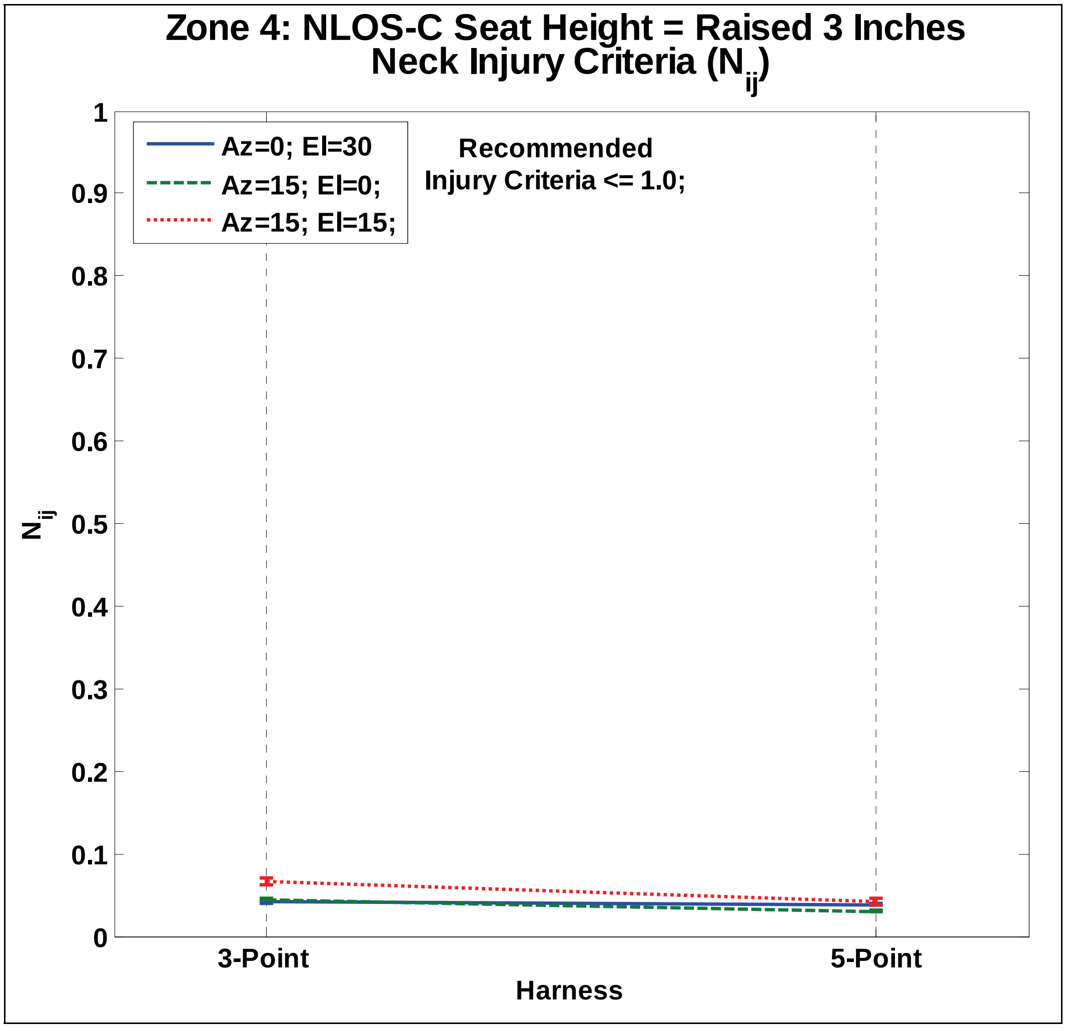

Figure 13. Zone 4 NLOS normal seat position N_{ij} by condition.

Sample time series data for the N_{ij} and the standard N_{ij} plot are presented for the azimuth = 15, elevation = 15, seat height = 3 inches, 3-pt harness condition are presented in figure 14. Similar data for the azimuth = 15, elevation = 15, seat height = +3 inches, 5-pt harness condition are presented in figure 15.

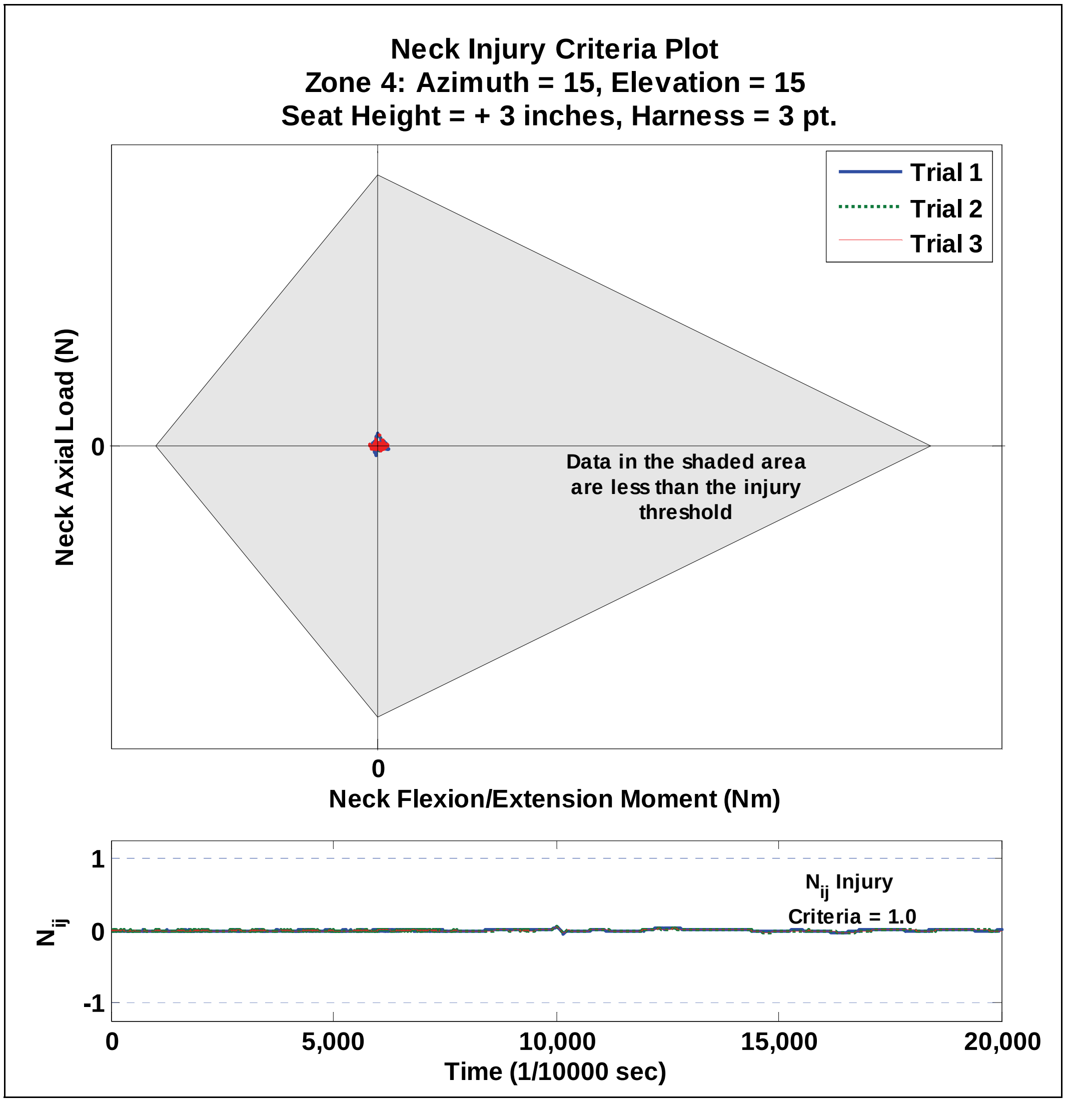

Figure 14. Sample N_{ij} time series data for the azimuth = 15 and elevation = 15, seat height = +3 inches, 3-pt harness condition.

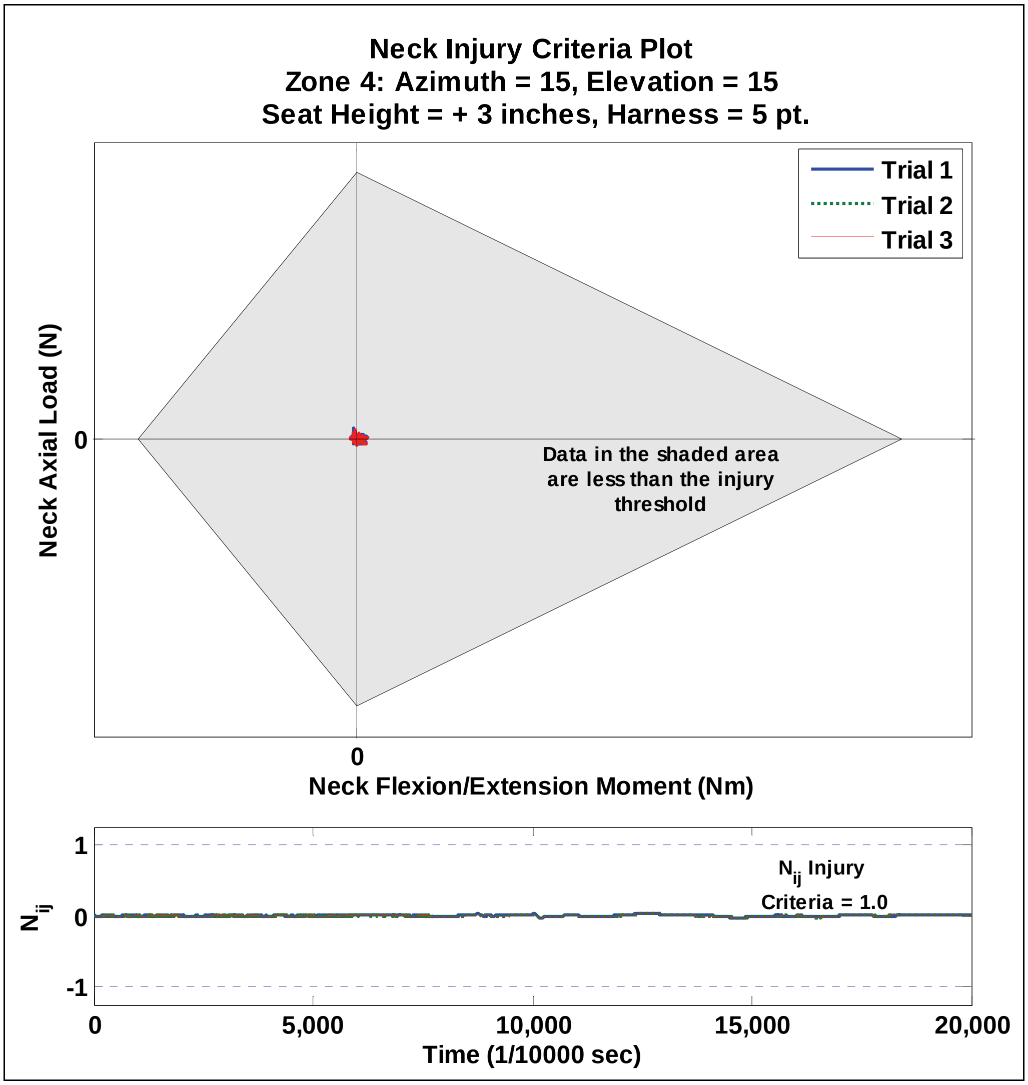

Figure 15. Sample N_{ij} time series data for the azimuth = 15 and elevation = 15, seat height = + 3 inches, 5-pt harness condition.

7.3 Zone 5, Seat Height Normal

There was no statistically significant main effect of azimuth (F = 0.561, p = 0.461), harness type (F = 2.222, p = 0.149) or Azimuth x Elevation interaction effect (F = 1.035, p = 0.371) on Hic_{15} (table 12). However, there was a significant main effect of elevation (F = 33.144, p = 0.000) on Hic_{15}. Similarly, there was no statistically significant main effect of azimuth (F = 0.013, p = 0.912) or Azimuth x Elevation interaction effect (F = 1.794, p = 0.188) on Hic_{36}. However, there was a significant main effect of elevation (F = 72.378, p = 0.000) and harness type (F = 56.383, p = 0.000) on Hic_{36}. For N_{ij}, no statistically significant effect of azimuth (F = 0.370, p = 0.549) or harness (F = 1.732, p = 0.201) was found; however, there was a statistically significant effect of elevation (F = 19.010, p = 0.000) and a statistically significant Azimuth x Elevation interaction (F = 9.327, p = 0.001).

Table 12. F-ratios and *p*-values for statistics on zone 5, seat height = normal

Effect of	**Hic_{15}**	**Hic_{36}**	**N_{ij}**
Condition (p-Value)	0.461	0.912	0.549
Condition (F-Ratio)	0.561	0.013	0.370
Harness (p-value)	0.000	0.000	0.000
Harness (F-Ratio)	33.144	72.378	19.010
Condition * harness (p-Value)	0.149	0.000	0.201
Condition * harness (F-Ratio)	2.222	56.383	1.732

Pairwise comparisons were performed to determine which elevations were statistically different from each other (table 13). Statistically significant differences were observed between all pairs of elevation conditions for HIC_{15} and HIC_{36} and between the elevation = 0 and 30 conditions and the elevation = 15 and 30 conditions for N_{ij}.

Table 13. *p*-values for pairwise comparisons: zone 5, seat height = normal.

p-values from pairwise comparisons: zone 5, seat height = normal				
Conditions		**Hic_{15}**	**Hic_{36}**	**N_{ij}**
0	15	0.000	0.000	0.069
0	30	0.000	0.000	0.000
15	30	0.004	0.000	0.000

Means (and standard error of the mean) for each azimuth, elevation, and harness condition for Hic_{15} are summarized in table 14 and shown in figure 16.

Table 14. Means (SEM) for seat = normal height: Hic_{15}.

		Elevation		
		0	15	30
3 pt. Harness	Azimuth = 0	2.347 (0.407)	6.505 (1.035)	3.639 (0.311)
	Azimuth = 15	3.623 (0.178)	4.631 (0.280)	4.665 (0.034)
5 pt. Harness	Azimuth = 0	2.194 (0.298)	4.399 (0.635)	4.564 (0.668)
	Azimuth = 15	2.822 (0.233)	5.839 (0.204)	4.414 (0.019)

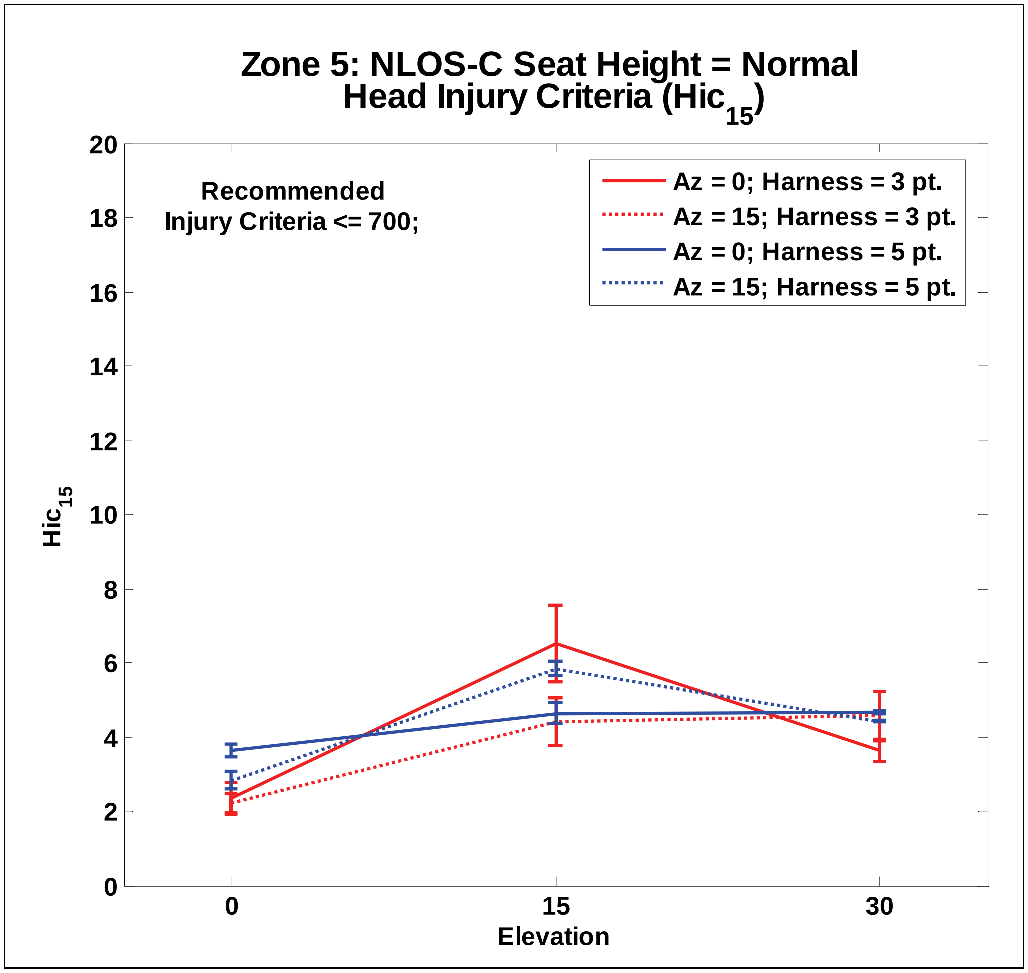

Figure 16. Zone 5: NLOS normal seat position Hic_{15} by elevation.

Means (and standard error of the means) for each condition and harness type for Hic_{36} are summarized in table 15 and shown in figure 17.

Table 15. Means (SEM) for seat = normal height: Hic_{36}.

		Elevation		
		0	15	30
3 pt. Harness	Azimuth = 0	3.948 (0.546)	8.430 (0.855)	5.783 (0.267)
	Azimuth = 15	6.233 (0.161)	9.752 (0.594)	8.711 (0.127)
5 pt. Harness	Azimuth = 0	3.284 (0.558)	7.187 (1.008)	7.199 (0.647)
	Azimuth = 15	5.268 (0.350)	11.251 (0.171)	8.461 (0.090)

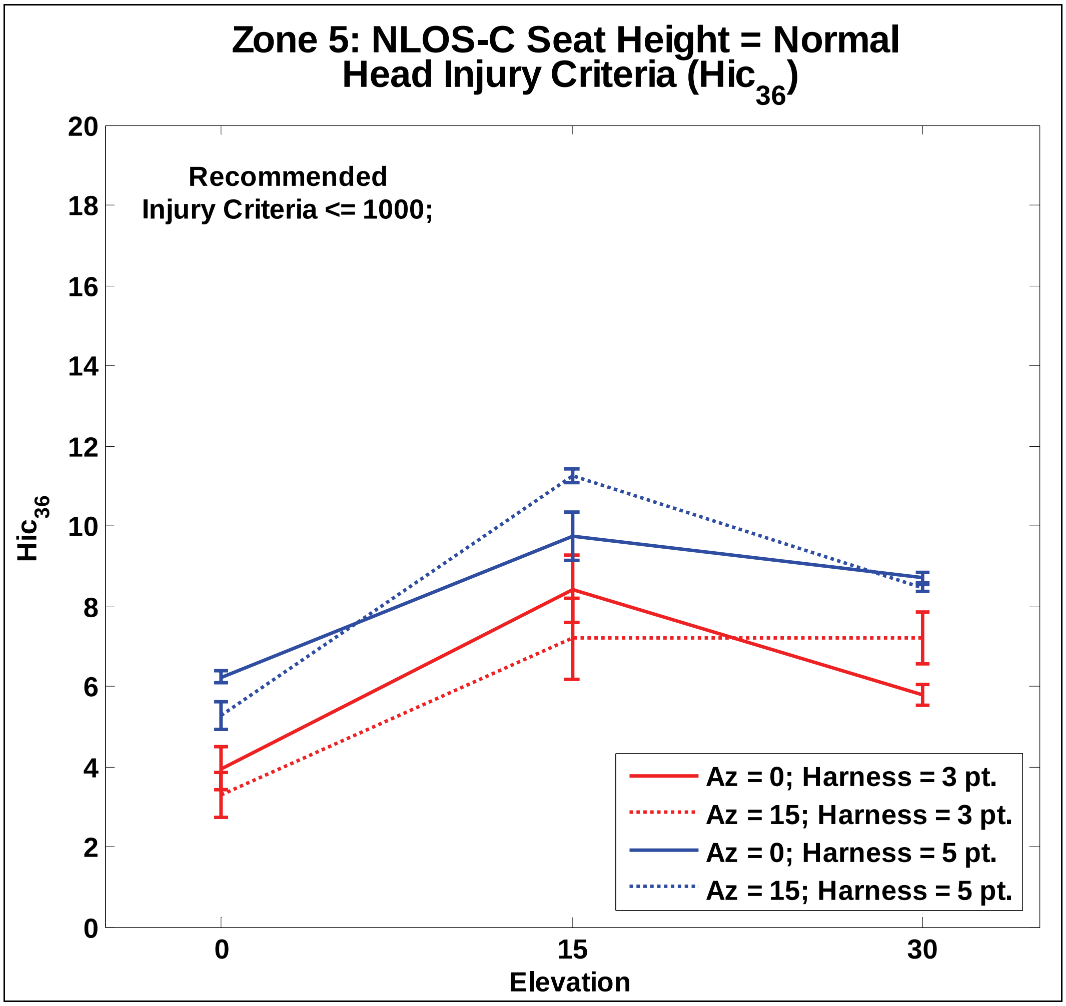

Figure 17. Zone 5: NLOS normal seat position Hic_{36} by elevation.

Sample resultant head acceleration, Hic_{15} and Hic_{36} time series data from the azimuth = 00, elevation = 15, seat height = normal, 3-pt harness condition are presented in figure 18. Similar data for the azimuth = 00, elevation = 30, seat height = normal, 3-pt harness condition are presented in figure 19, and data for the azimuth = 15, elevation = 30, seat height = normal, 3-pt harness condition are presented in figure 20.

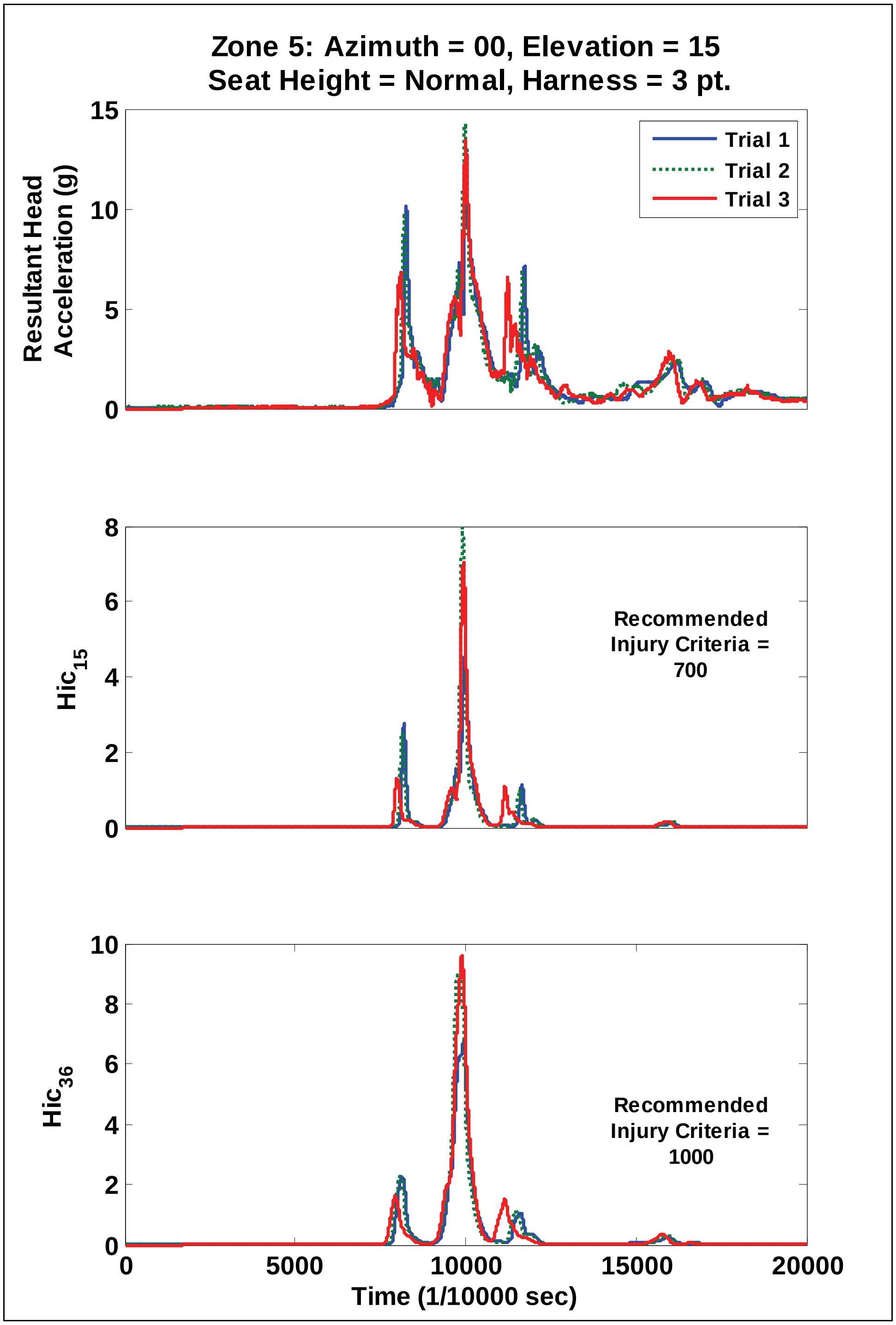

Figure 18. Zone 5: sample head acceleration, Hic_{15} and Hic_{36} time series data for the azimuth = 00 and elevation = 15, seat height = normal, 3-pt harness condition.

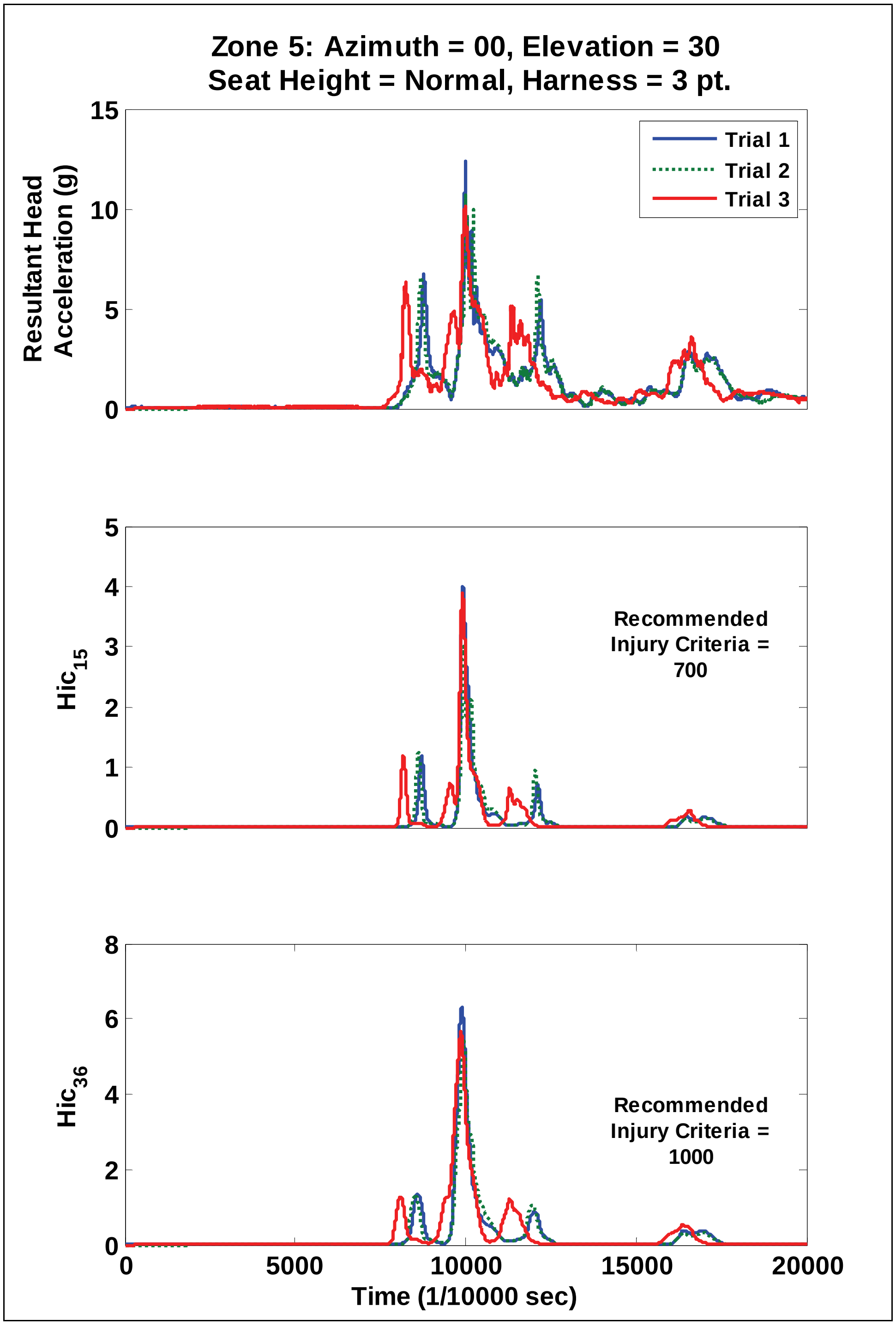

Figure 19. Zone 5: sample head acceleration, Hic_{15} and Hic_{36} time series data for the azimuth = 00 and elevation = 30, seat height = normal, 3-pt harness condition.

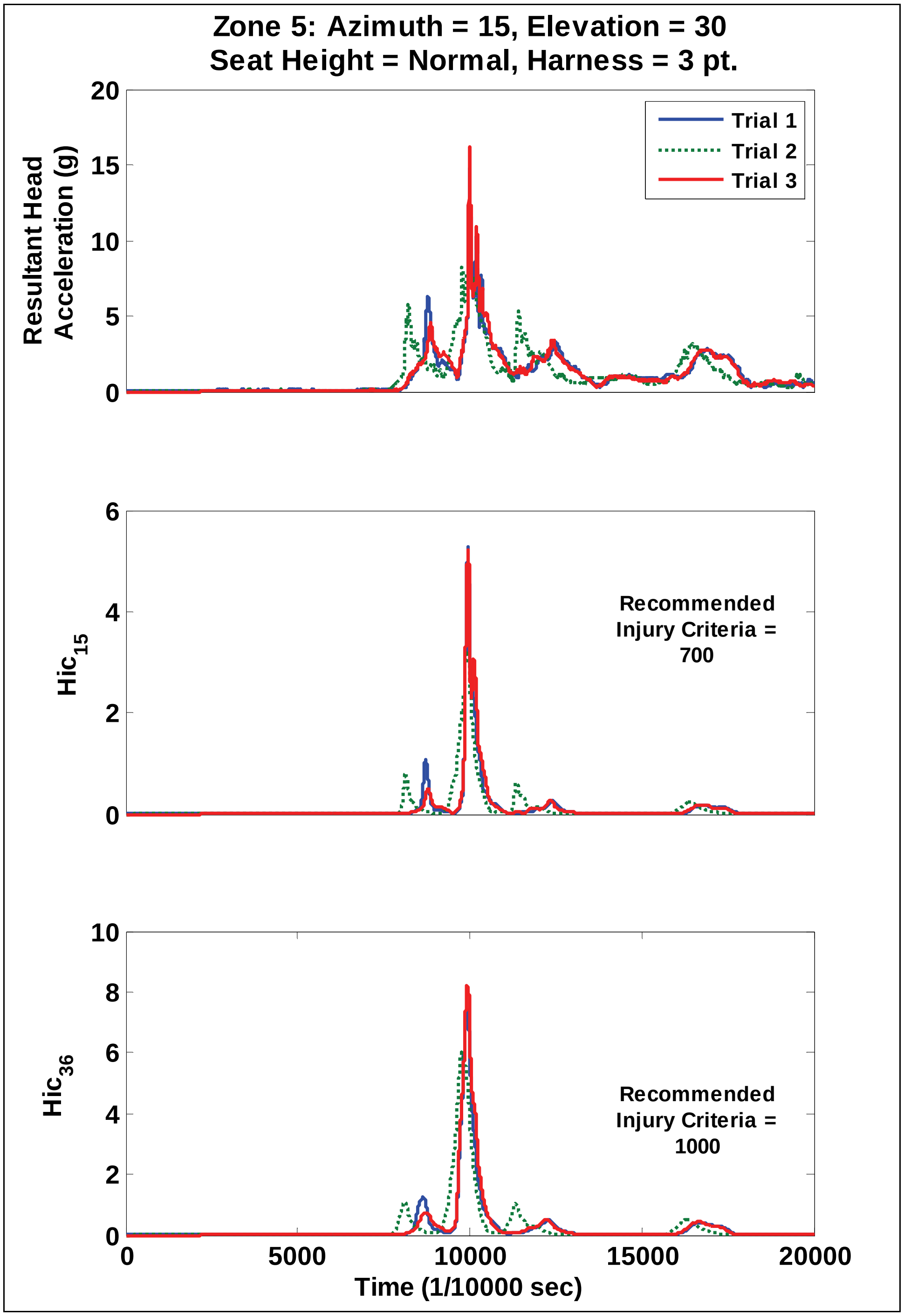

Figure 20. Zone 5: sample head acceleration, Hic_{15} and Hic_{36} time series data for the azimuth = 15 and elevation = 30, seat height = normal, 3-pt harness condition.

Additionally, sample resultant head acceleration, Hic_{15} and Hic_{36} time series data from the azimuth = 00, elevation = 15, seat height = normal, 5-pt harness condition are presented in figure 21. Similar data for the azimuth = 00, elevation = 30, seat height = normal, 5-pt harness condition are presented in figure 22, and data for the azimuth = 15, elevation = 30, seat height = normal, 5-pt harness condition are presented in figure 23.

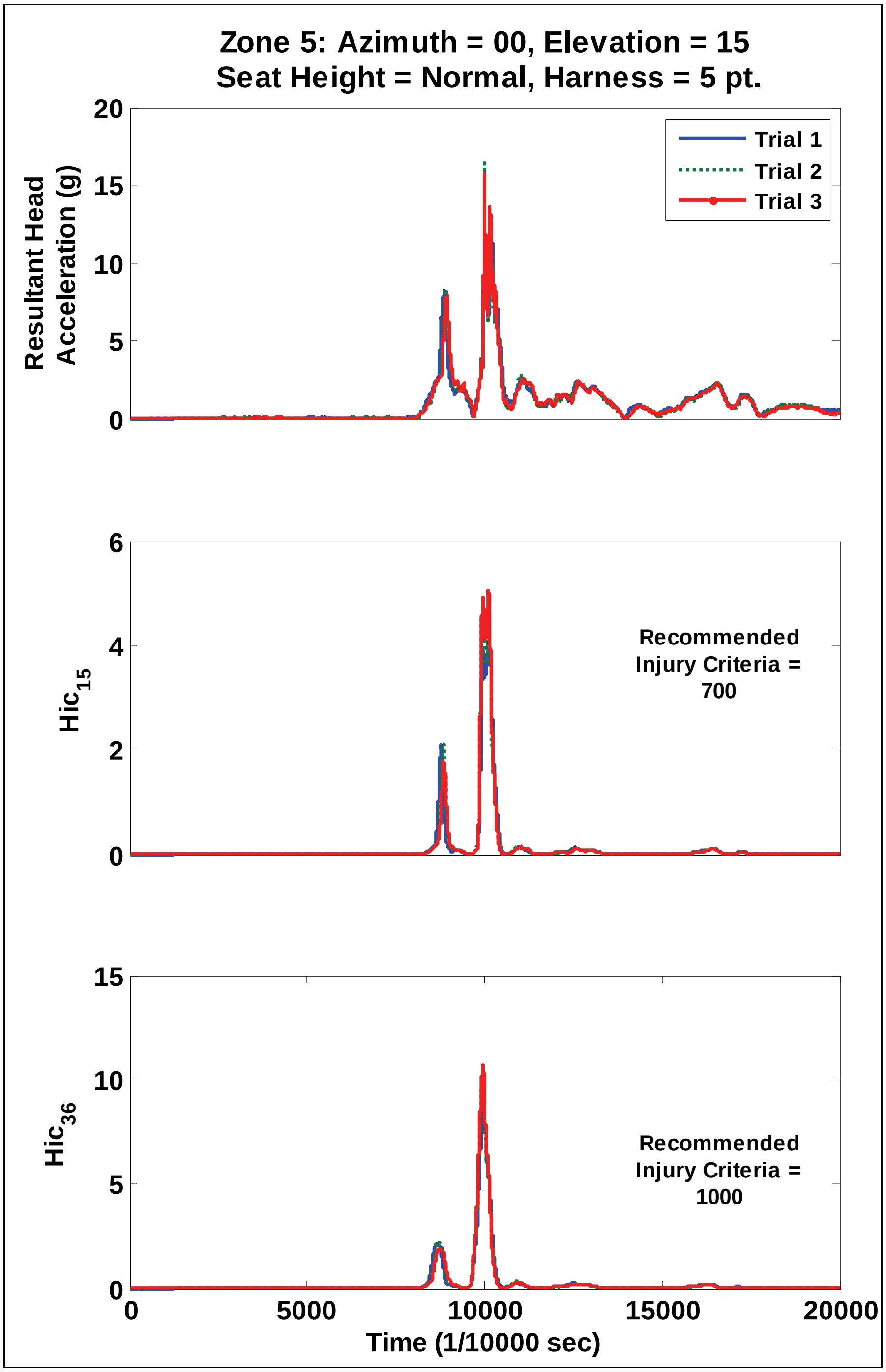

Figure 21. Zone 5: sample head acceleration, Hic_{15} and Hic_{36} time series data for the azimuth = 00 and elevation = 15, seat height = normal, 5-pt harness condition.

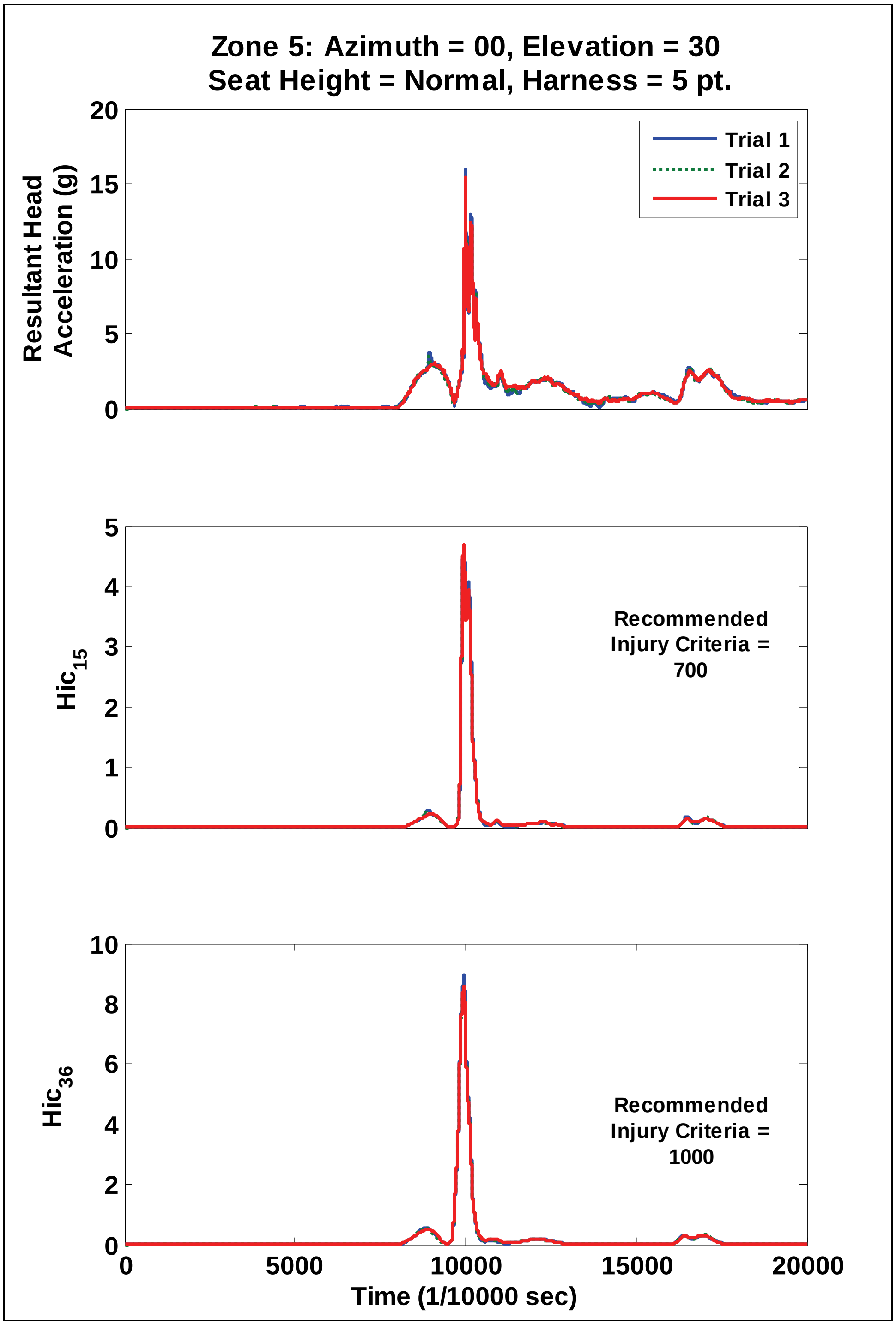

Figure 22. Zone 5: sample head acceleration, Hic_{15} and Hic_{36} time series data for the azimuth = 00 and elevation = 30, seat height = normal, 5-pt harness condition.

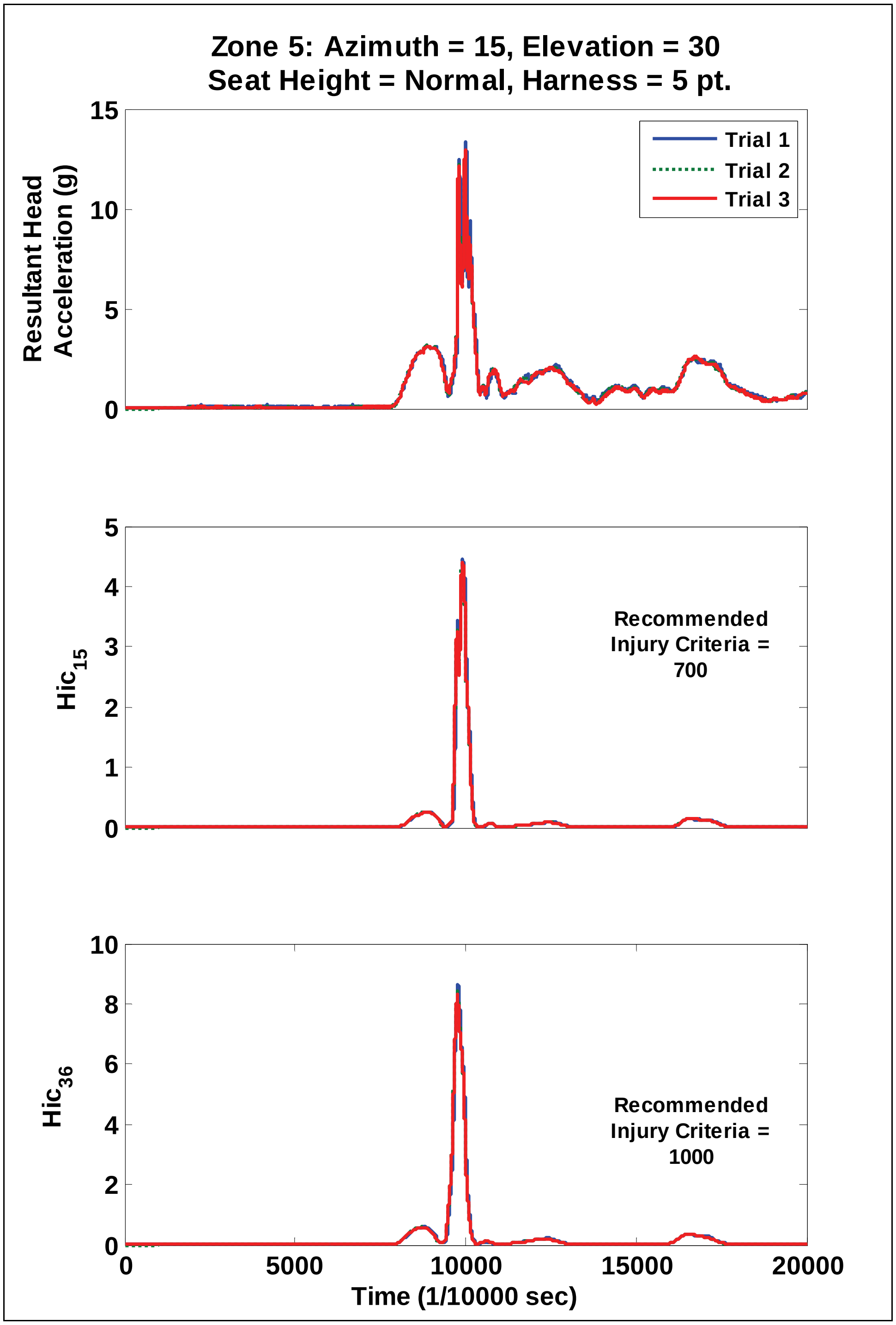

Figure 23. Zone 5: sample head acceleration, Hic_{15} and Hic_{36} time series data for the azimuth = 15 and elevation = 30, seat height = normal, 5-pt harness condition.

Means (and standard error of the mean) for each azimuth, elevation, and harness condition for Hic_{15} are summarized in table 16 and shown in figure 24.

Table 16. Means (SEM) for seat = normal height: N_{ij}.

		Elevation		
		0	15	30
3 pt. Harness	Azimuth = 0	0.156 (0.008)	0.173 (0.007)	0.230 (0.025)
	Azimuth = 15	0.164 (0.004)	0.145 (0.009)	0.250 (0.003)
5 pt. Harness	Azimuth = 0	0.165 (0.014)	0.217 (0.027)	0.223 (0.019)
	Azimuth = 15	0.169 (0.005)	0.192 (0.003)	0.182 (0.006)

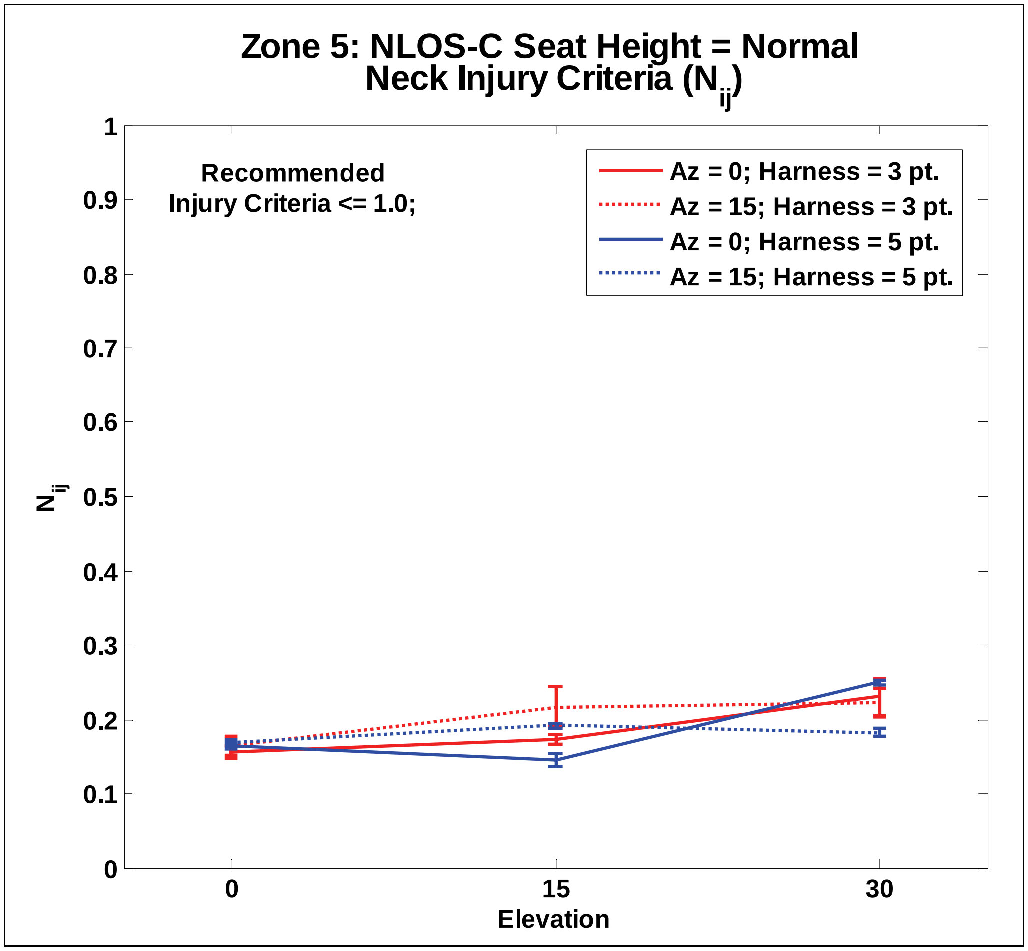

Figure 24. Zone 5: NLOS normal seat position N_{ij} by elevation.

Sample N_{ij} time series data and the standard N_{ij} plot from the azimuth = 00, elevation = 15, seat height = normal, 3-pt harness condition are presented in figure 25. Similar data for the azimuth = 00, elevation = 30, seat height = normal, 3-pt harness condition are presented in figure 26, and data for the azimuth = 15, elevation = 30, seat height = normal, 3-pt harness condition are presented in figure 27.

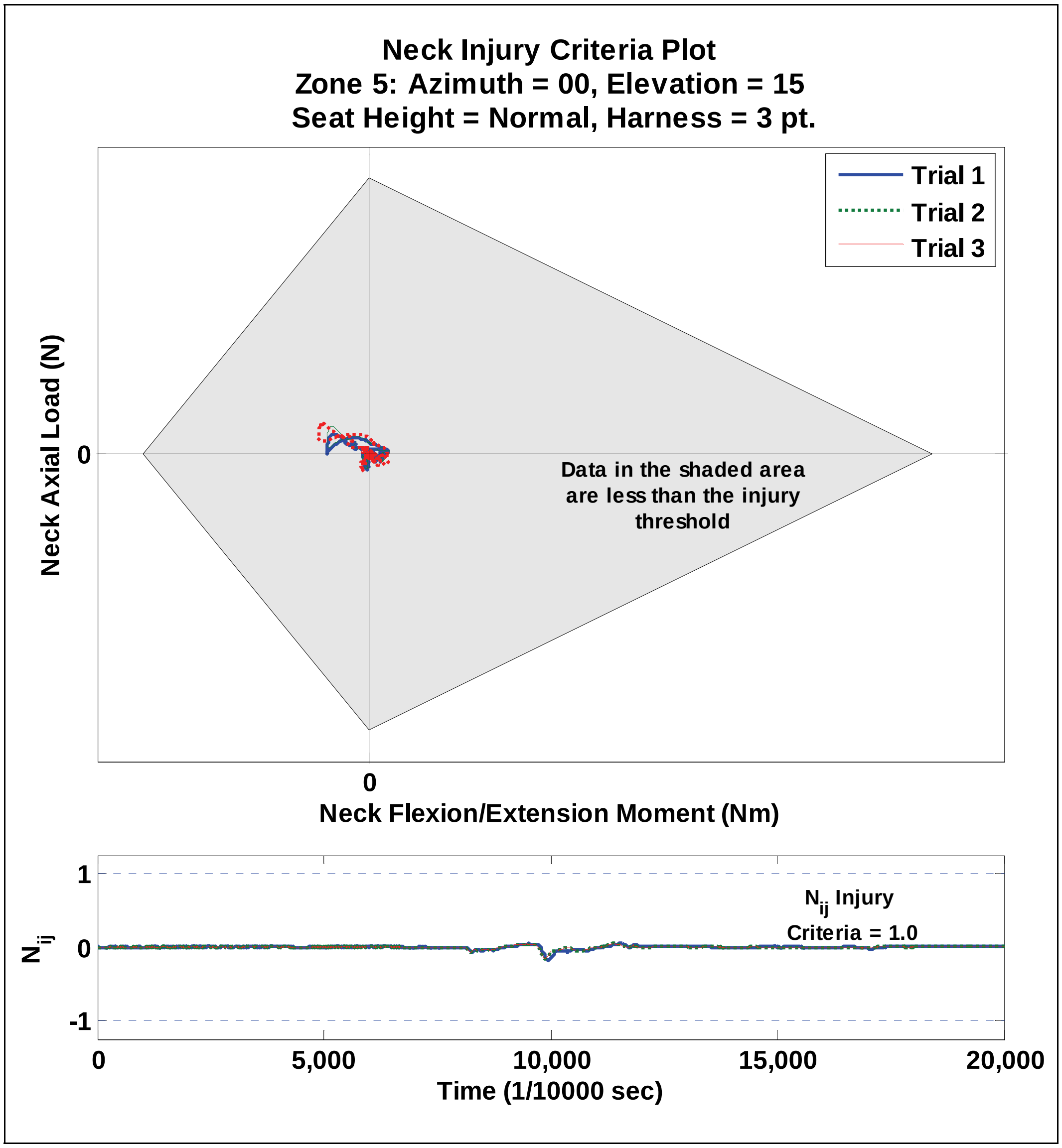

Figure 25. Zone 5: sample N_{ij} time series data for the azimuth = 00 and elevation = 15, seat height = normal, 3-pt harness condition.

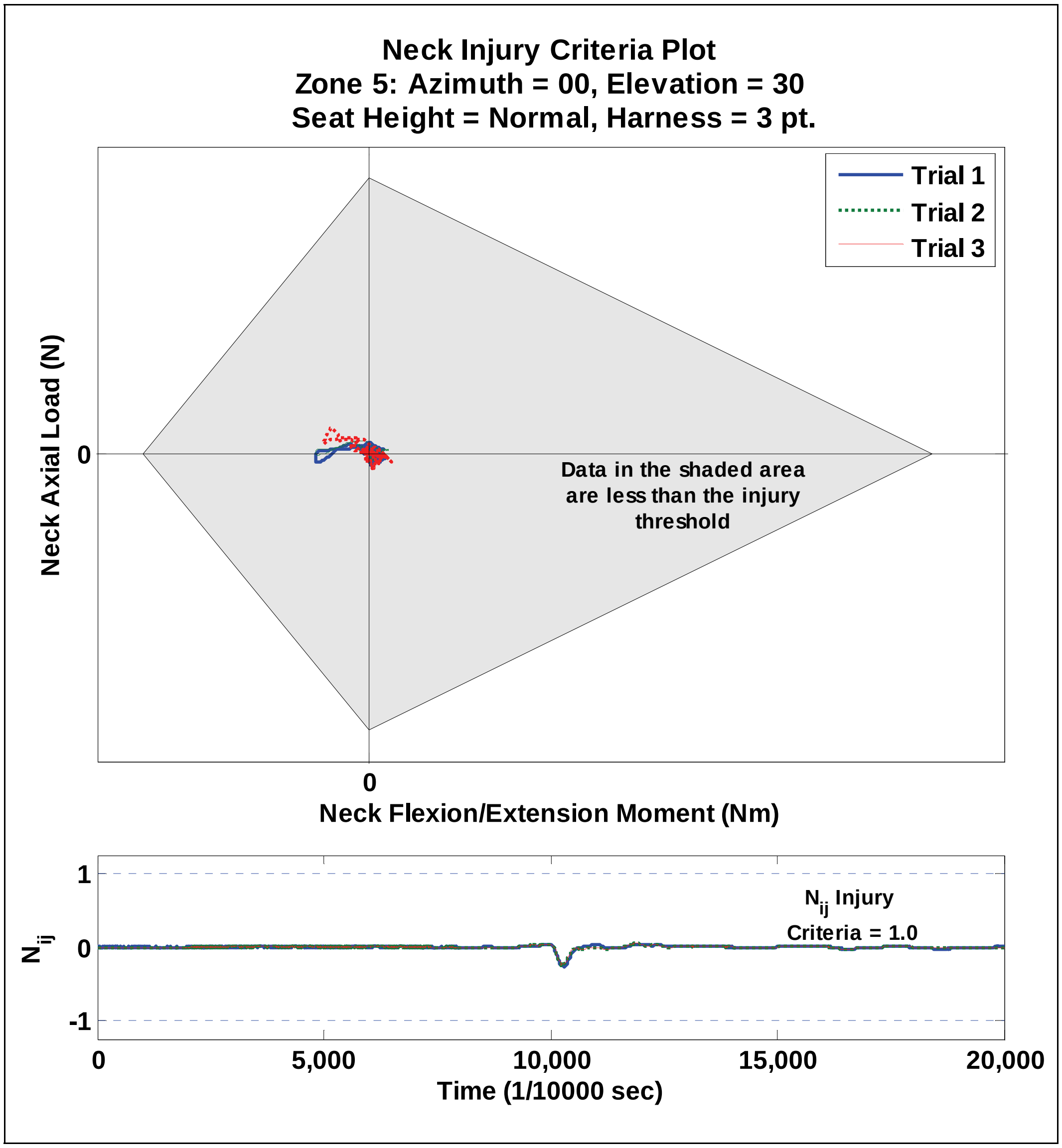

Figure 26. Zone 5: sample N_{ij} time series data for the azimuth = 00 and elevation = 30, seat height = normal, 3-pt harness condition.

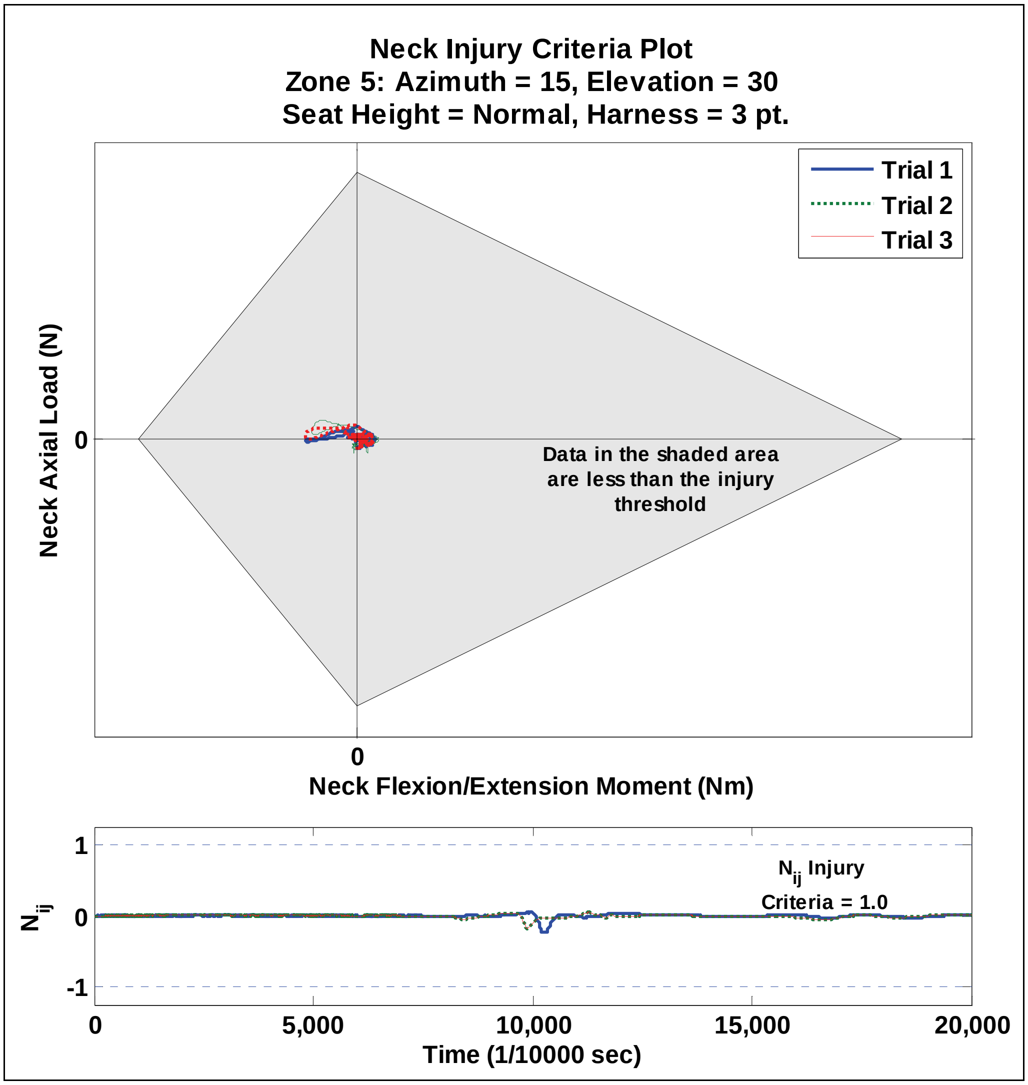

Figure 27. Zone 5: sample N_{ij} time series data for the azimuth = 15 and elevation = 30, seat height = normal, 3-pt harness condition.

Sample N_{ij} time series data and the standard N_{ij} plot from the azimuth = 00, elevation = 15, seat height = normal, 5-pt harness condition are presented in figure 28. Similar data for the azimuth = 00, elevation = 30, seat height = normal, 5-pt harness condition are presented in figure 29, and data for the azimuth = 15, elevation = 30, seat height = normal, 5-pt harness condition are presented in figure 30.

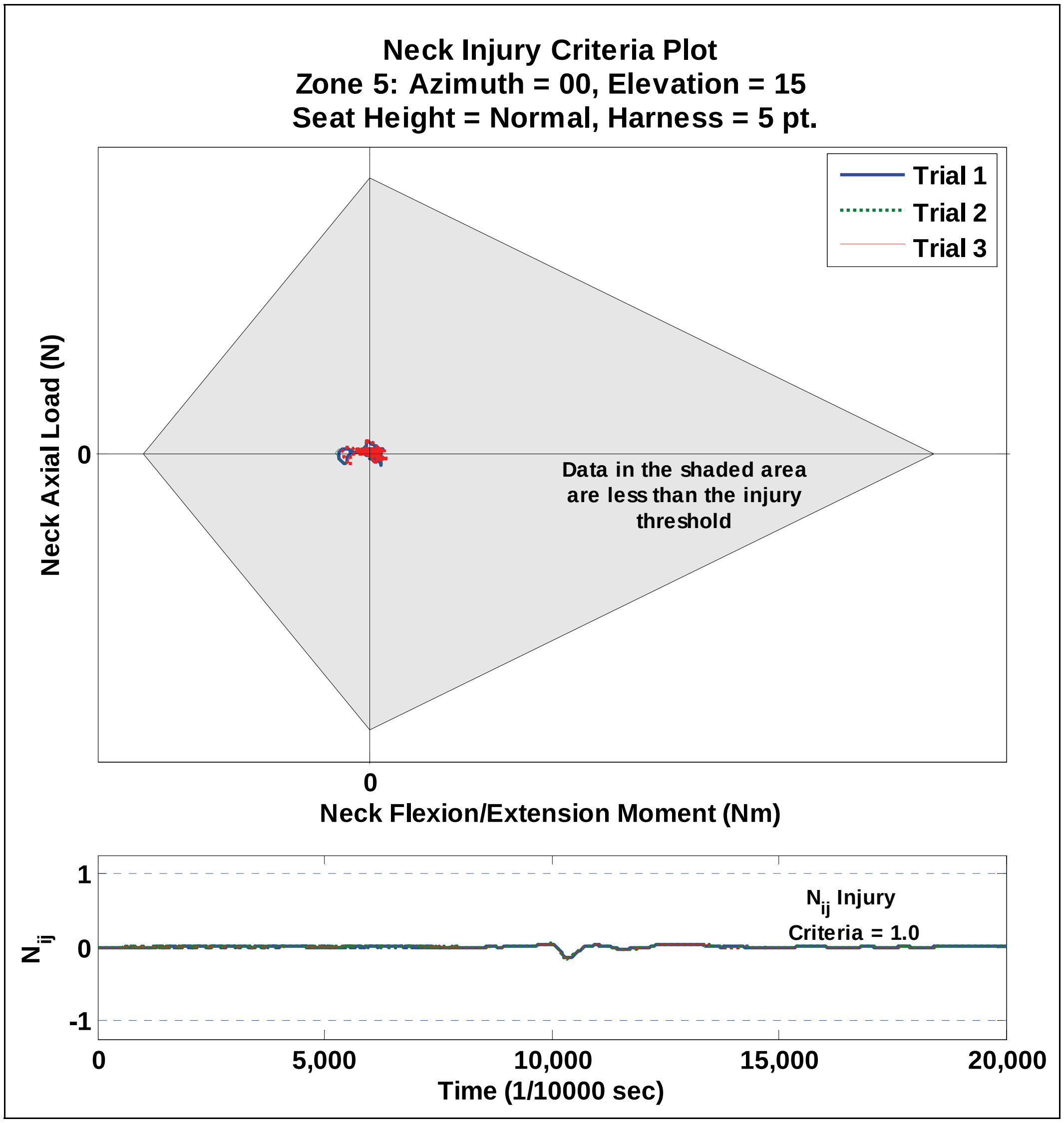

Figure 28. Zone 5: sample N_{ij} time series data for the azimuth = 00 and elevation = 15, seat height = normal, 5-pt harness condition.

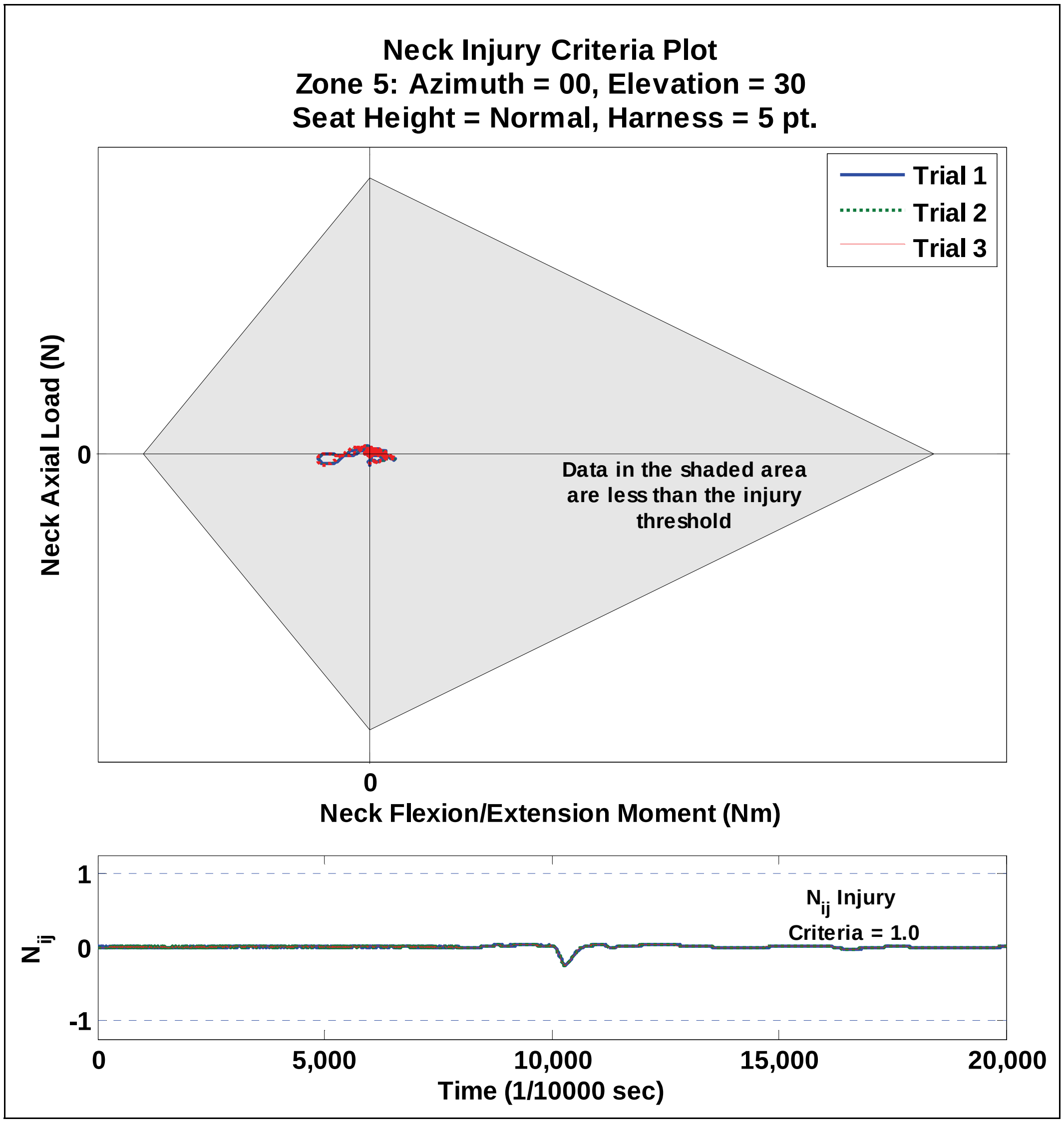

Figure 29. Zone 5: sample N_{ij} time series data for the azimuth = 00 and elevation = 30, seat height = normal, 5-pt harness condition.

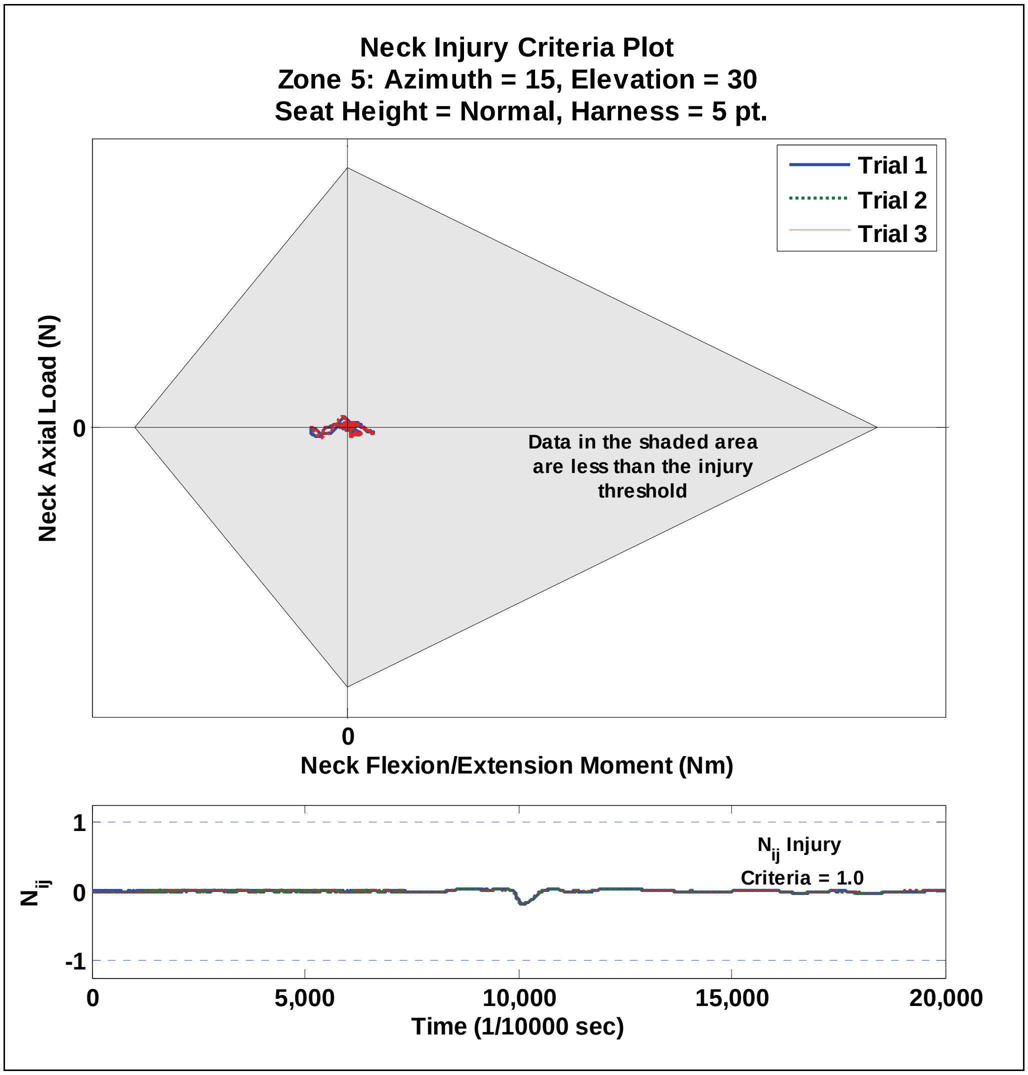

Figure 30. Zone 5: sample N_{ij} time series data for the azimuth = 15 and elevation = 30, seat height = normal, 5-pt harness condition.

7.4 Zone 5, Seat Height Raised 3 Inches

There was a statistically significant main effect of azimuth (F = 18.498, p = 0.000), elevation (F = 43.061, p = 0.000) and of harness type (F = 5.286, p = 0.031) on Hic_{15} (table 17). However, there was no statistically significant Azimuth x Elevation interaction (F = 5.268, p = 0.670) on Hic_{15}. Similarly, there was a statistically significant main effect of azimuth (F = 12.862, p = 0.000), elevation (F = 52.030, p = 0.000) and of harness type (F = 57.223, p = 0.000) on Hic_{36}, but there was no statistically significant Azimuth x Elevation interaction (F = 2.934, p = 0.072) on Hic_{36}. Results were similar for N_{ij}; there was a statistically significant main effect of azimuth (F = 14.433, p = 0.001), elevation (F = 9.931, p = 0.001) and of harness type (F = 4.240, p = 0.050) on N_{ij}, but there was no statistically significant Azimuth x Elevation interaction (F = 1.479, p = 0.248) on N_{ij}.

Table 17. F-ratios and *p*-values for statistics on zone 5, seat height = raised 3 inches.

Effect of	**Hic_{15}**	**Hic_{36}**	**N_{ij}**
Condition (p-Value)	0.000	0.000	0.001
Condition (F-Ratio)	18.498	12.862	14.433
Harness (p-value)	0.000	0.000	0.001
Harness (F-Ratio)	43.061	52.030	9.931
Condition * harness (p-Value)	0.031	0.000	0.050
Condition * harness (F-Ratio)	5.268	57.223	4.240

Pairwise comparisons were performed to determine which elevations were statistically different from each other (table 18). Statistically significant differences were found between the 0-degrees-of-elevation condition and both the 15- and 30-degrees-of-elevation conditions for HIC_{15} and HIC_{36}. No statistically significant differences were observed between the 15-degrees-of-elevation and 30-degrees-of-elevation conditions. For N_{ij}, statistically significant differences were observed between the 15-degrees-of-elevation condition and both the 0- and 30-degrees-of-elevation conditions but not between the 0- and 30-degrees-of-elevation conditions.

Table 18. *p*-values for pairwise comparisons: zone 5, seat height = raised 3 inches.

p-values from pairwise comparisons: zone 5, seat height = raised 3 inches				
Conditions		**Hic_{15}**	**Hic_{36}**	**N_{ij}**
0	15	0.000	0.000	0.000
0	30	0.000	0.000	0.000
15	30	0.004	0.196	0.063

Means (and standard error of the mean) for each azimuth, elevation, and harness condition for Hic_{15} are summarized in table 19 and shown in figure 31.

Table 19. Means (SEM) for seat = raised 3 inches: Hic_{15}.

		Elevation		
		0	15	30
3 pt. Harness	Azimuth = 0	9.775 (0.315)	12.846 (0.390)	15.878 (0.818)
	Azimuth = 15	7.268 (0.501)	11.158 (0.236)	11.561 (0.457)
5 pt. Harness	Azimuth = 0	6.777 (0.863)	10.962 (0.585)	9.857 (1.747)
	Azimuth = 15	8.095 (0.066)	11.140 (0.151)	11.400 (0.291)

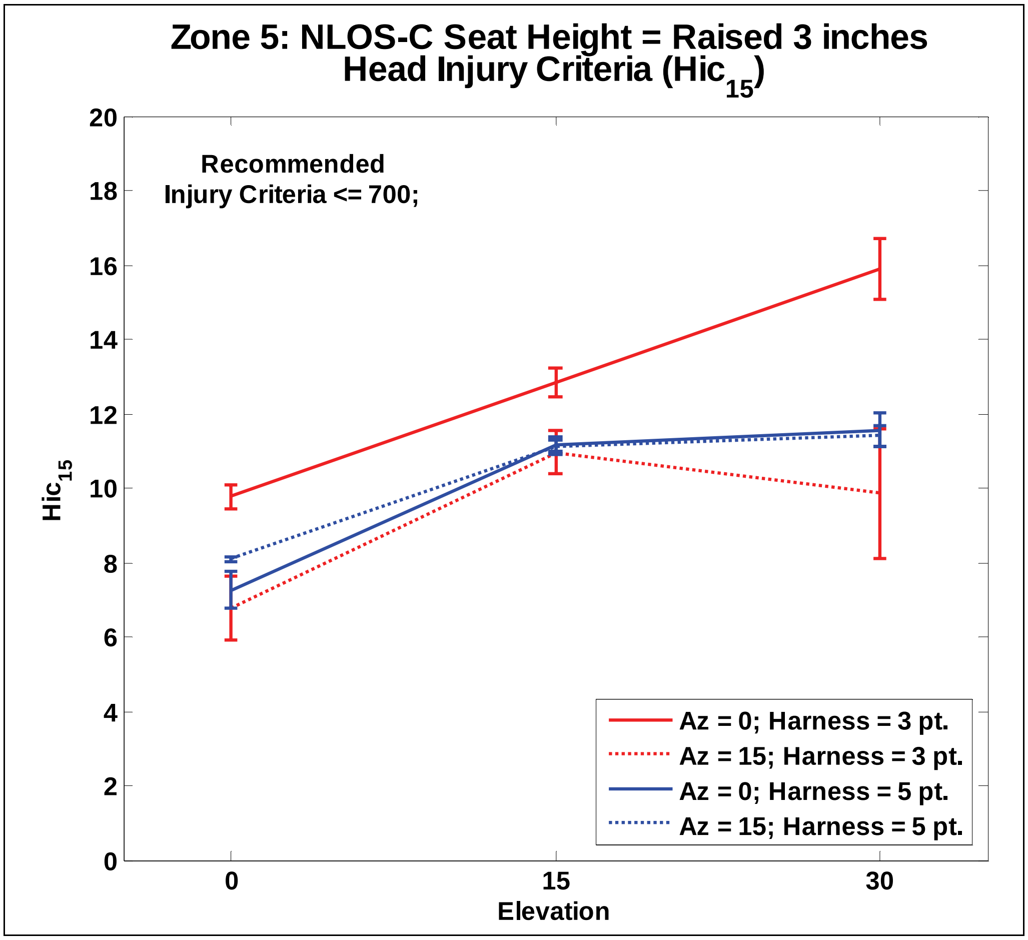

Figure 31. Zone 5: NLOS normal seat position Hic_{15} by elevation.

Means (and standard error of the means) for each condition and harness type for Hic_{36} are summarized in table 20 and shown in figure 32.

Table 20. Means (SEM) for seat = raised 3 inches: Hic_{36}.

		Elevation		
		0	15	30
3 pt. Harness	Azimuth = 0	7.238 (0.101)	10.461 (0.788)	12.602 (0.712)
	Azimuth = 15	4.893 (0.146)	6.932 (0.169)	7.984 (0.117)
5 pt. Harness	Azimuth = 0	5.364 (0.496)	9.235 (0.135)	8.837 (1.351)
	Azimuth = 15	5.127 (0.060)	7.450 (0.139)	7.559 (0.104)

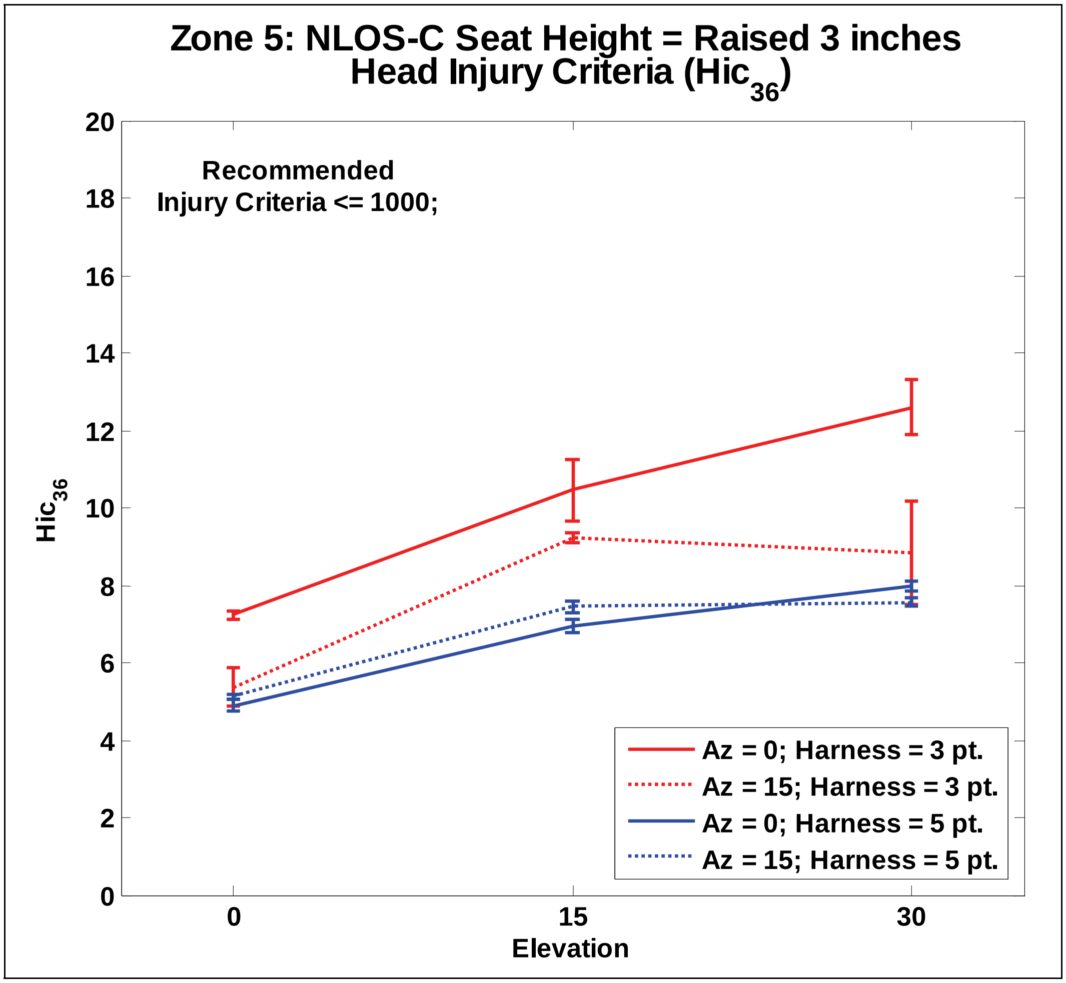

Figure 32. Zone 5: NLOS normal seat position Hic_{36} by elevation.

Sample resultant head acceleration, Hic_{15} and Hic_{36} time series data from the azimuth = 00, elevation = 15, seat height = raised 3 inches, 5-pt harness condition are presented in figure 33. Similar data for the azimuth = 00, elevation = 30, seat height = raised 3 inches, 5-pt harness condition are presented in figure 34, and data for the azimuth = 15, elevation = 30, seat height = raised 3 inches, 5-pt harness condition are presented in figure 35.

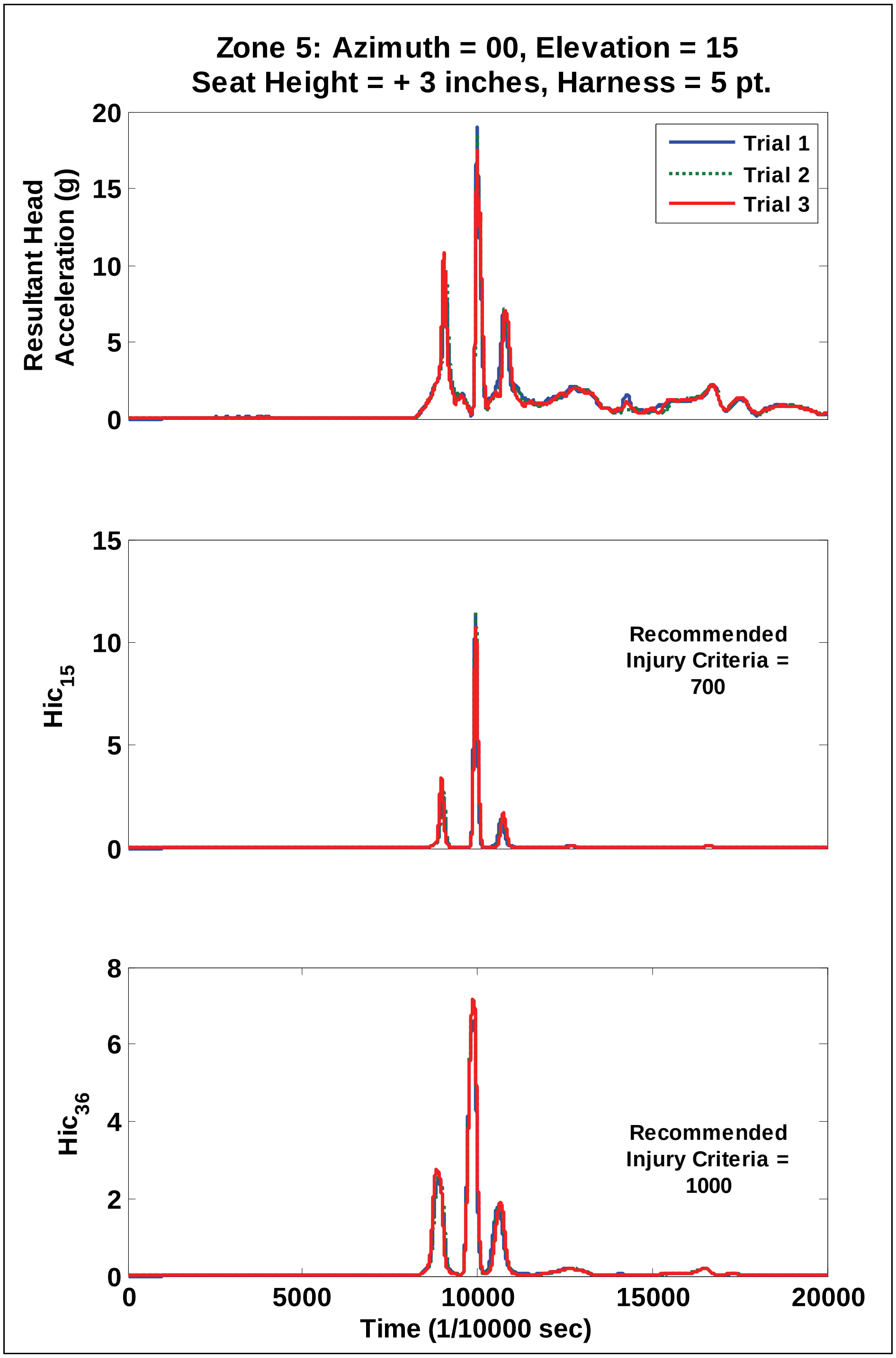

Figure 33. Zone 5: sample head acceleration, Hic_{15} and Hic_{36} time series data for the azimuth = 00 and elevation = 15, seat height = raised 3 inches, 5-pt harness condition.

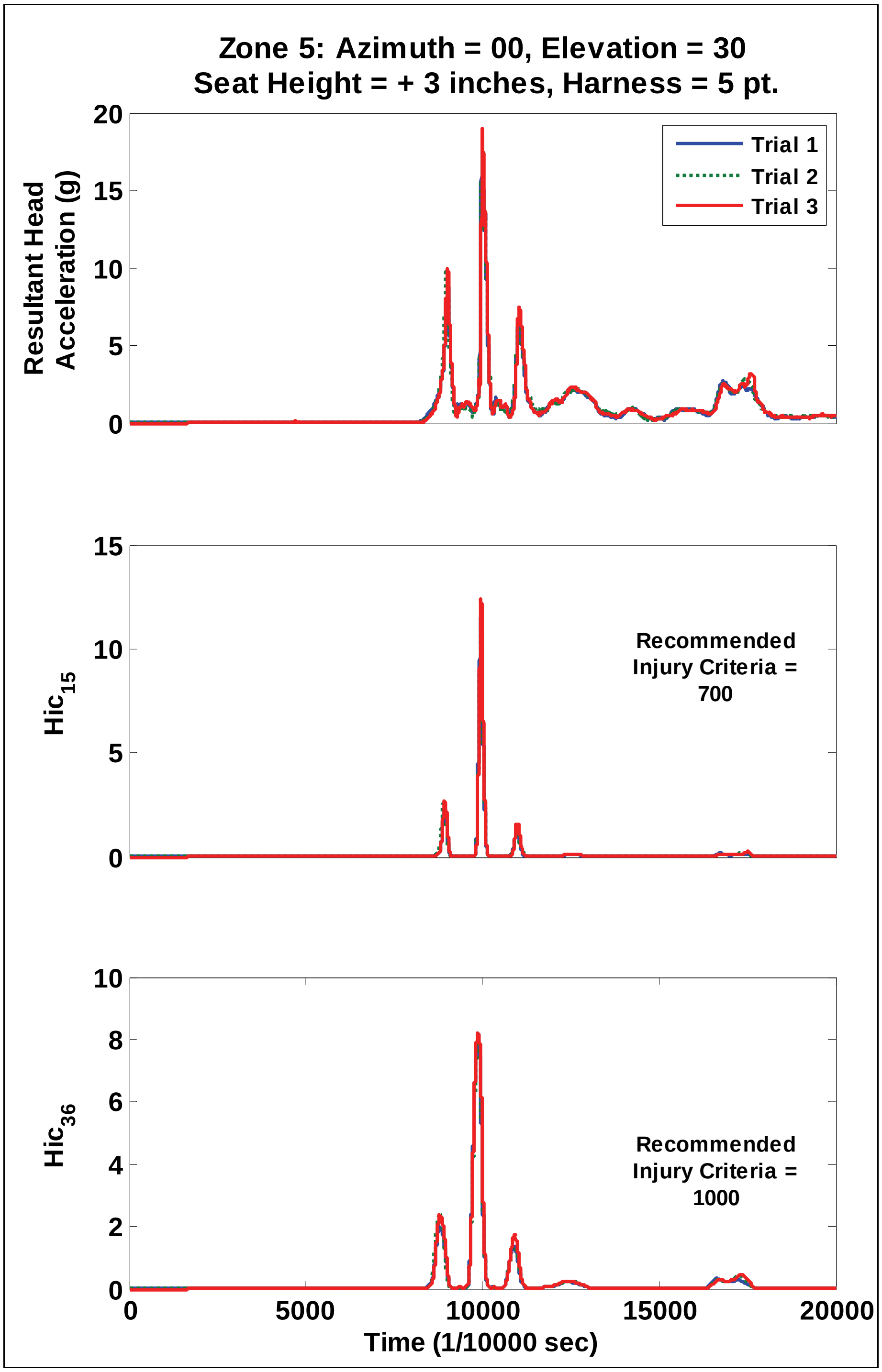

Figure 34. Zone 5: sample head acceleration, Hic_{15} and Hic_{36} time series data for the azimuth = 00 and elevation = 30, seat height = raised 3 inches, 5-pt harness condition.

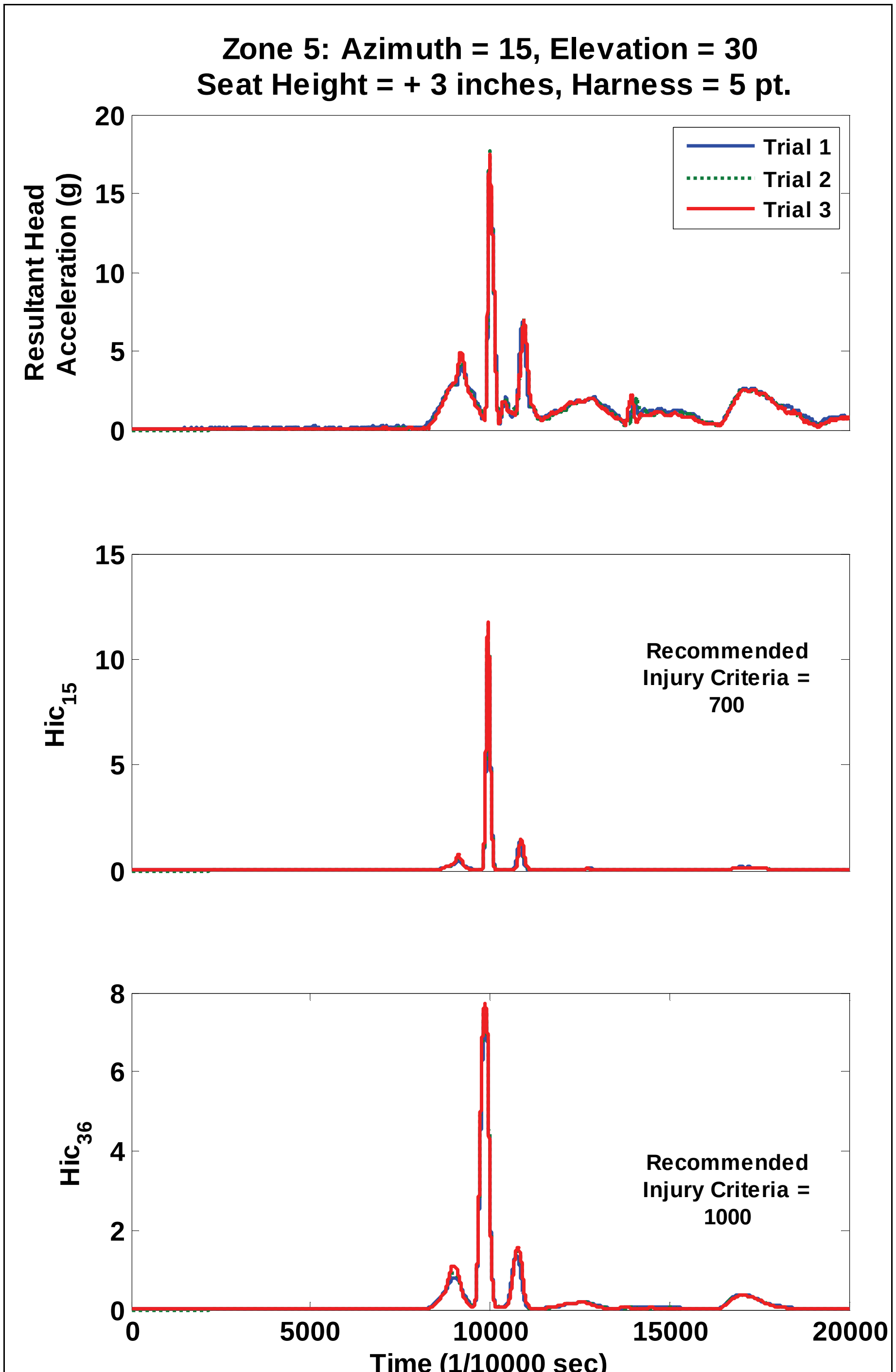

Figure 35. Zone 5: sample head acceleration, Hic_{15} and Hic_{36} time series data for the azimuth = 15 and elevation = 30, seat height = raised 3 inches, 5-pt harness condition.

Means (and standard error of the mean) for each azimuth, elevation, and harness condition for N_{ij} are summarized in table 21 and shown in figure 36.

Table 21. Means (SEM) for seat = raised 3 inches: N_{ij}.

		Elevation		
		0	15	30
3 pt. Harness	Azimuth = 0	0.076 (0.002)	0.091 (0.003)	0.075 (0.004)
	Azimuth = 15	0.062 (0.006)	0.070 (0.001)	0.069 (0.004)
5 pt. Harness	Azimuth = 0	0.064 (0.001)	0.066 (0.002)	0.061 (0.001)
	Azimuth = 15	0.068 (0.003)	0.078 (0.002)	0.063 (0.006)

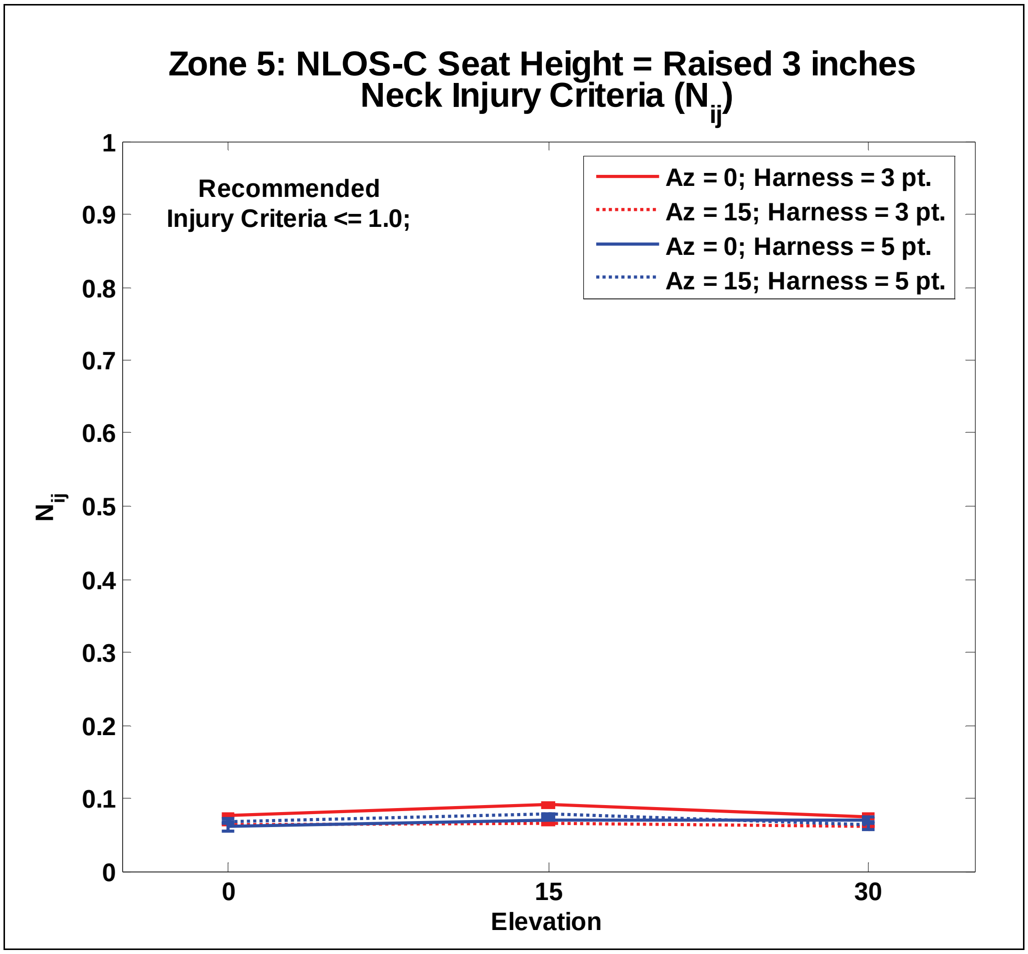

Figure 36. Zone 5: NLOS normal seat position N_{ij} by elevation.

Sample N_{ij} time series data and the standard N_{ij} plot from the azimuth = 00, elevation = 15, seat height = raised 3 inches, 3-pt harness condition are presented in figure 37. Similar data for the azimuth = 00, elevation = 30, seat height = raised 3 inches, 3-pt harness condition are presented in figure 38, and data for the azimuth = 15, elevation = 30, seat height = raised 3 inches, 3-pt harness condition are presented in figure 39.

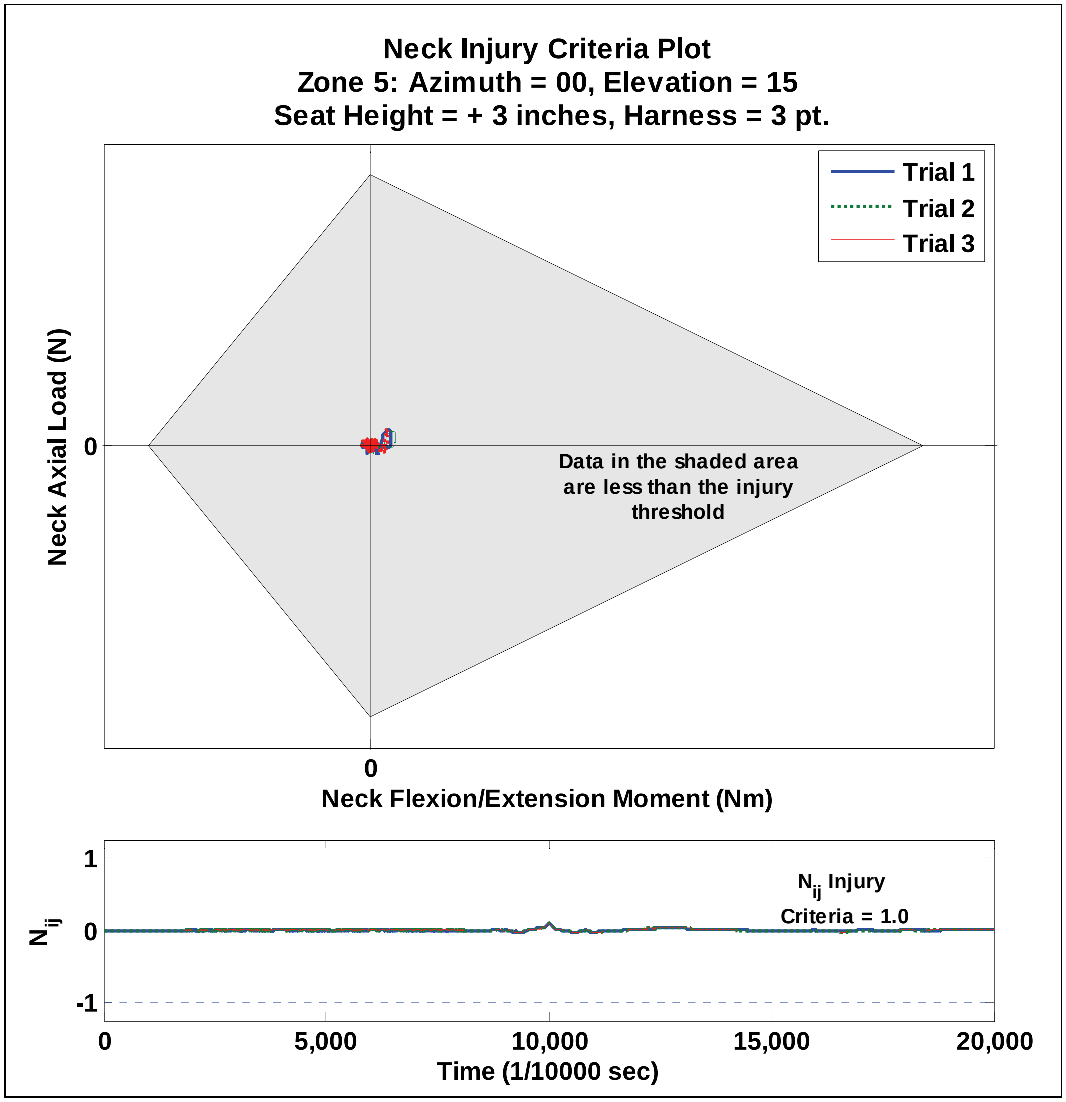

Figure 37. Zone 5: sample N_{ij} time series data for the azimuth = 00 and elevation = 15, seat height = raised 3 inches, 3-pt harness condition.

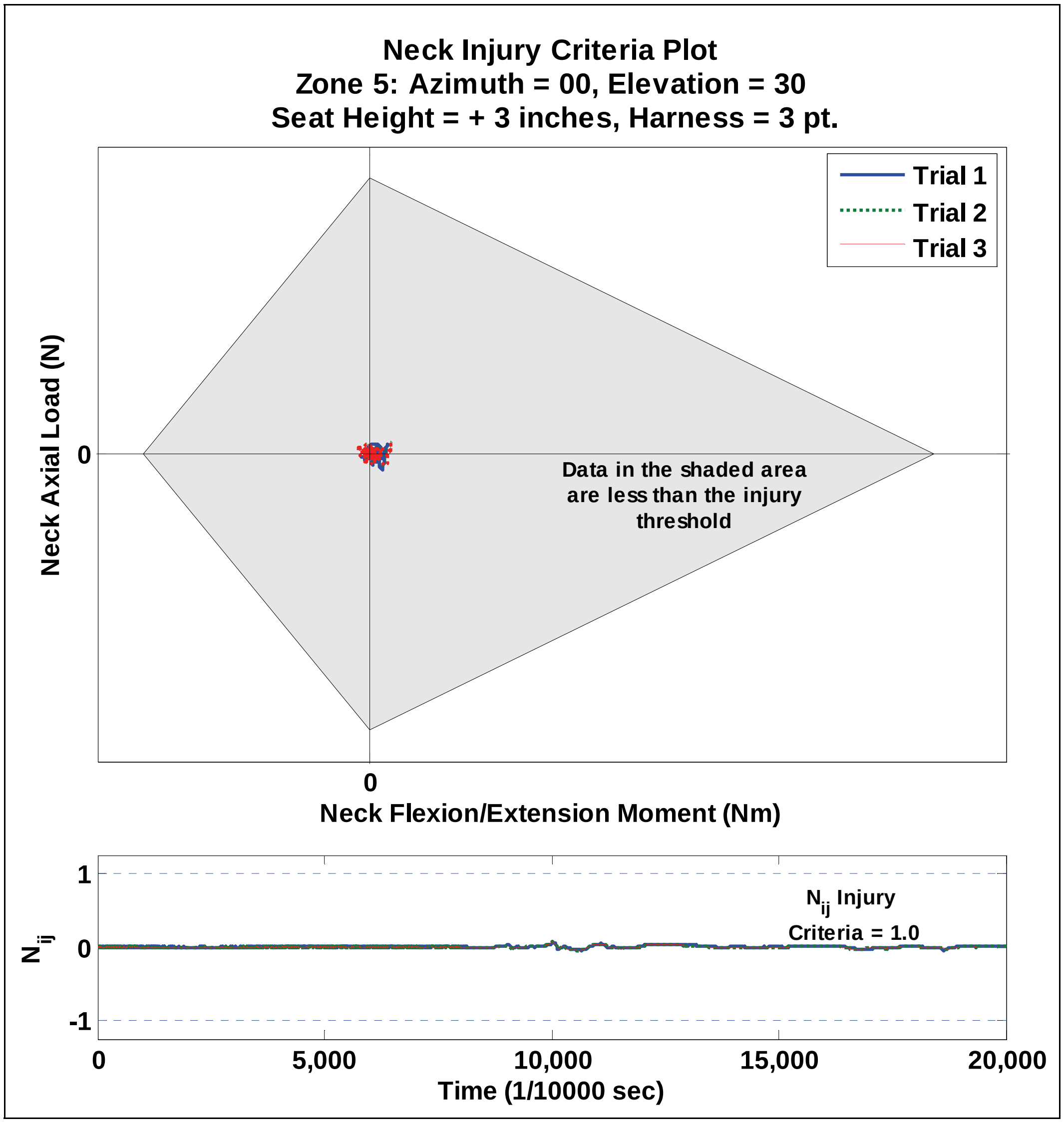

Figure 38. Zone 5: sample N_{ij} time series data for the azimuth = 00 and elevation = 30, seat height = raised 3 inches, 3-pt harness condition.

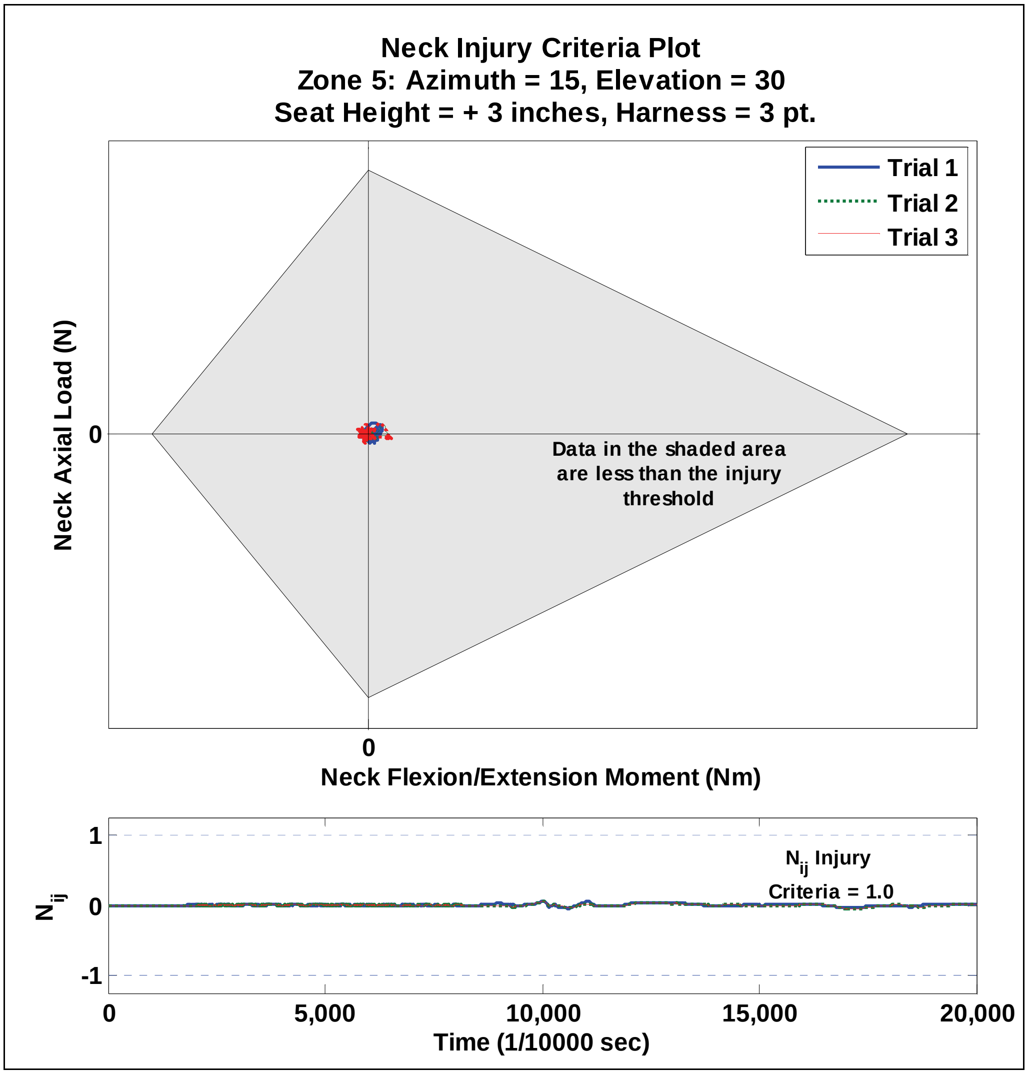

Figure 39. Zone 5: sample N_{ij} time series data for the azimuth = 15 and elevation = 30, seat height = raised 3 inches, 3-pt harness condition.

Sample N_{ij} time series data and the standard N_{ij} plot from the azimuth = 00, elevation = 15, seat height = raised 3 inches, 5-pt harness condition are presented in figure 40. Similar data for the azimuth = 00, elevation = 30, seat height = raised 3 inches, 5-pt harness condition are presented in figure 41, and data for the azimuth = 15, elevation = 30, seat height = raised 3 inches, 5-pt harness condition are presented in figure 42.

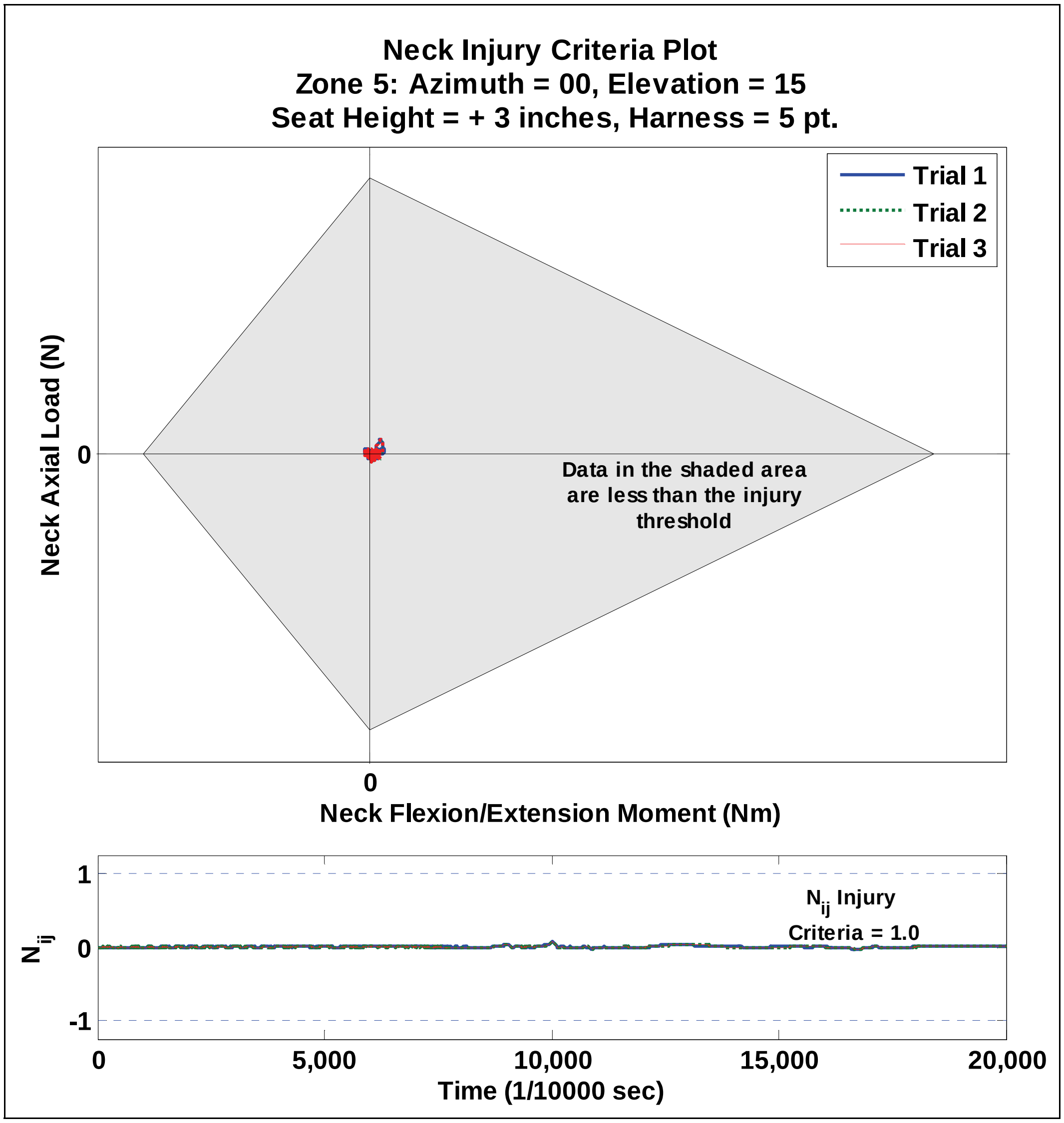

Figure 40. Zone 5: sample N_{ij} time series data for the azimuth = 00 and elevation = 15, seat height = raised 3 inches, 5-pt harness condition.

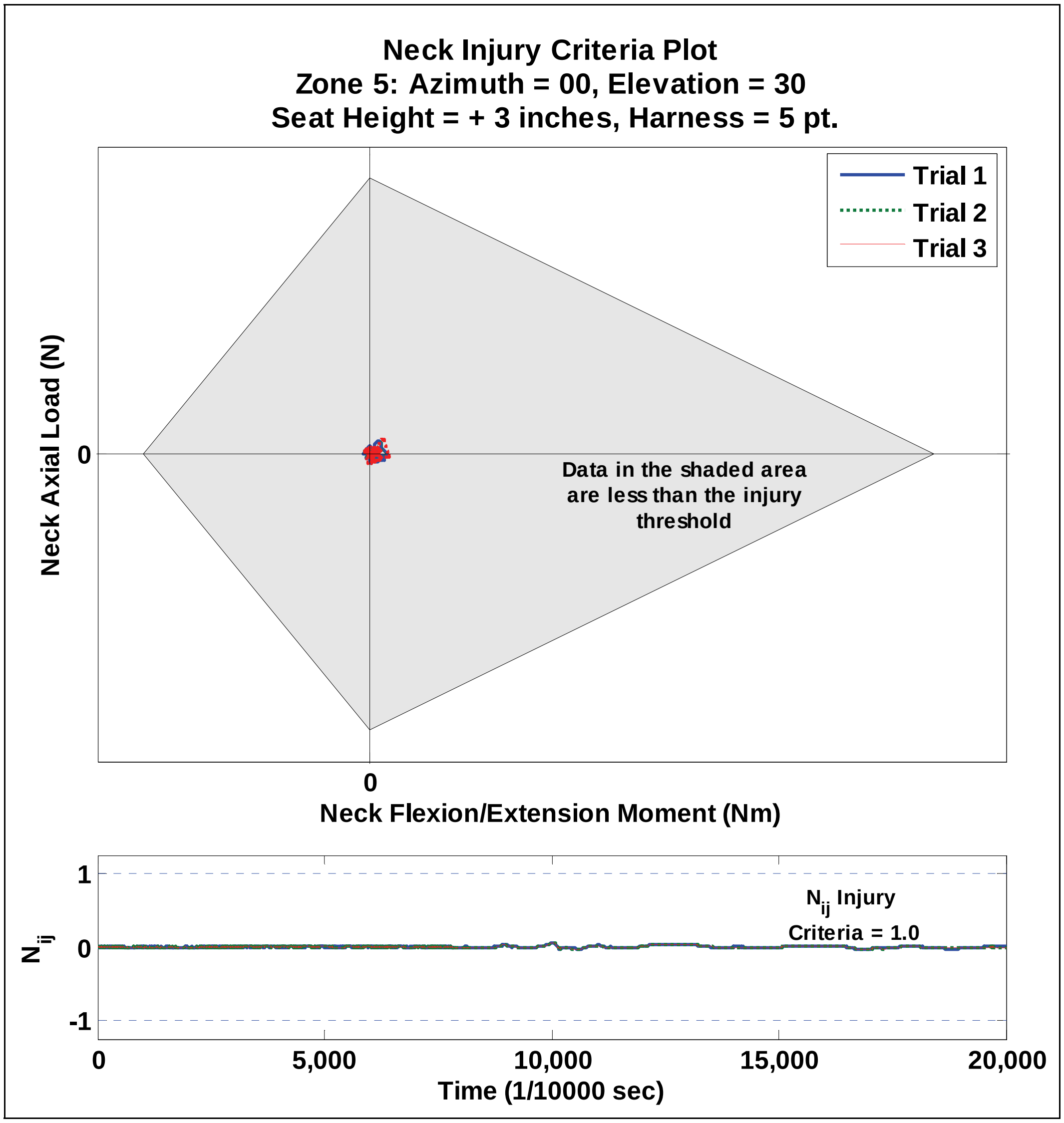

Figure 41. Zone 5: sample N_{ij} time series data for the azimuth = 00 and elevation = 30, seat height = raised 3 inches, 5-pt harness condition.

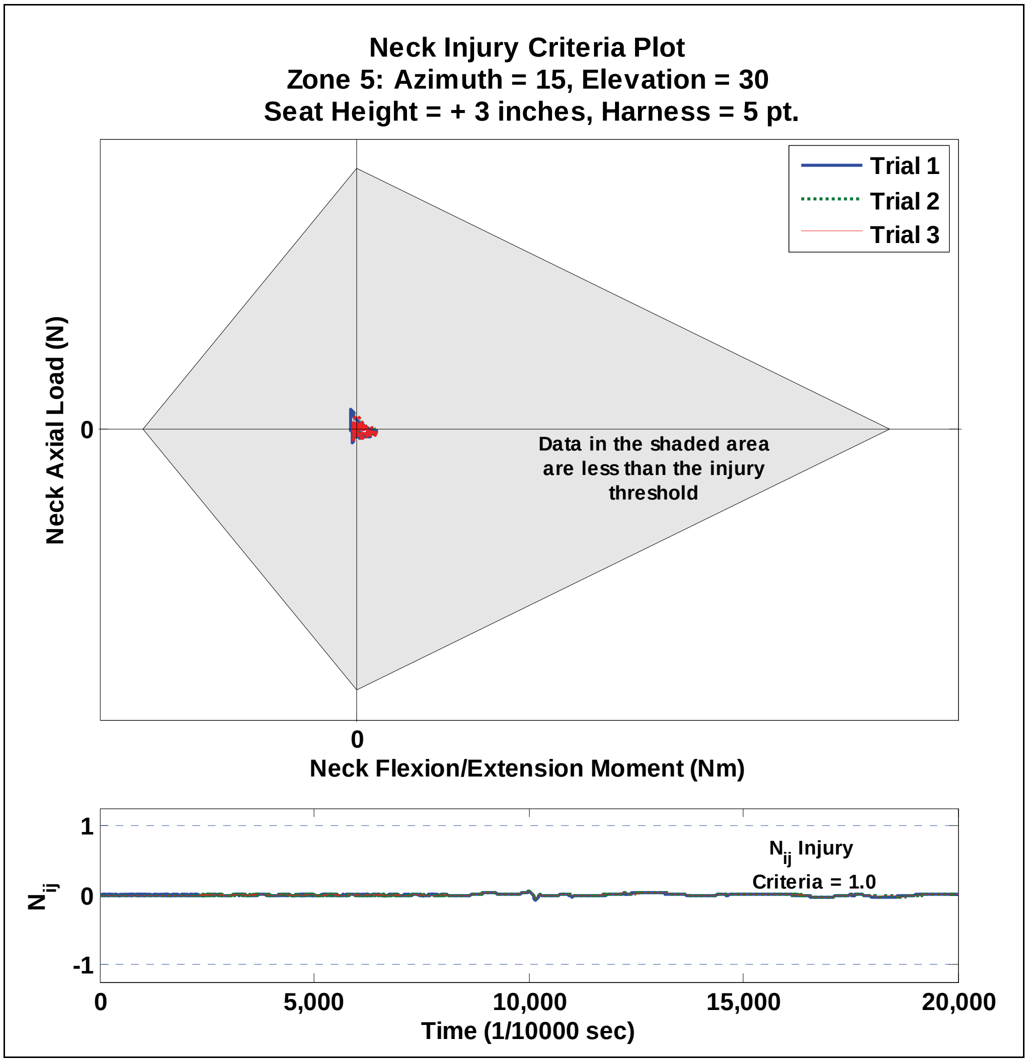

Figure 42. Zone 5: sample N_{ij} time series data for the azimuth = 15 and elevation = 30, seat height = raised 3 inches, 5-pt harness condition.

7.5 Probability of Injury

The probability of head injury was calculated, based on equation 4 for Zones 4 and 5 and for both seat height conditions. For Zone 4, the probability of moderate head injury ranged from a high of 4 in 10,000,000 to about 2.7 in 1,000,000,000,000,000, so obviously the potential of moderate head injury was fairly low. Similar results were found for Zone 5; the probability of moderate head injury ranged from about 3.8 in 10,000,000 to about 4.1 in 10,000,000,000,000. In contrast, for both Zones 4 and 5, the probability of neck injury was much higher (figures 43 and 44). The probability of neck injury was calculated from the equations in table 1, but only the results for moderate and critical injuries are presented.

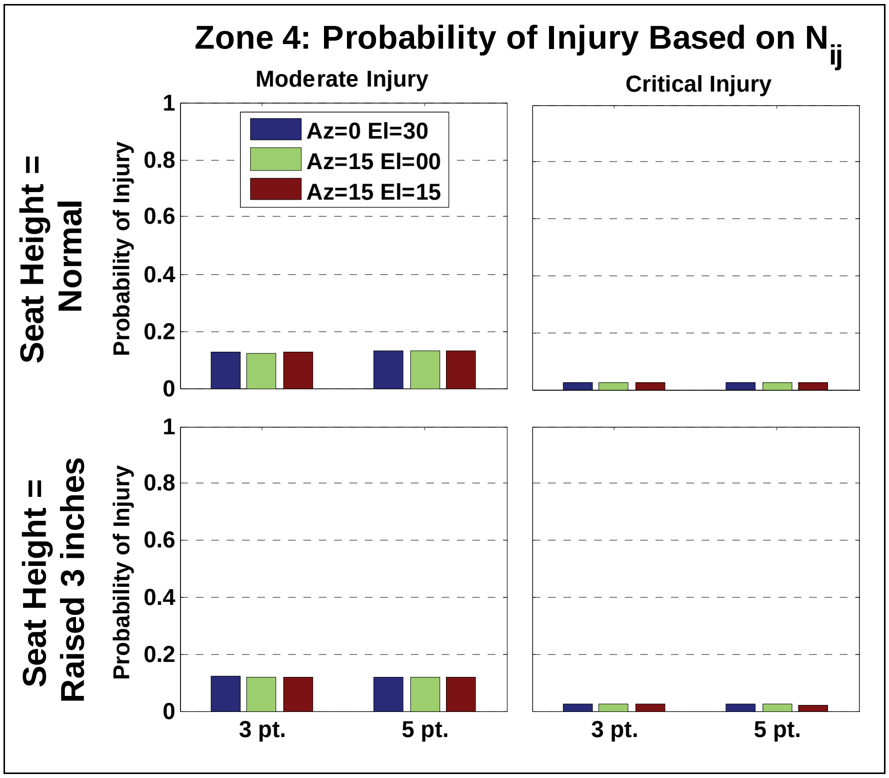

Figure 43. Zone 4 probability of neck injury.

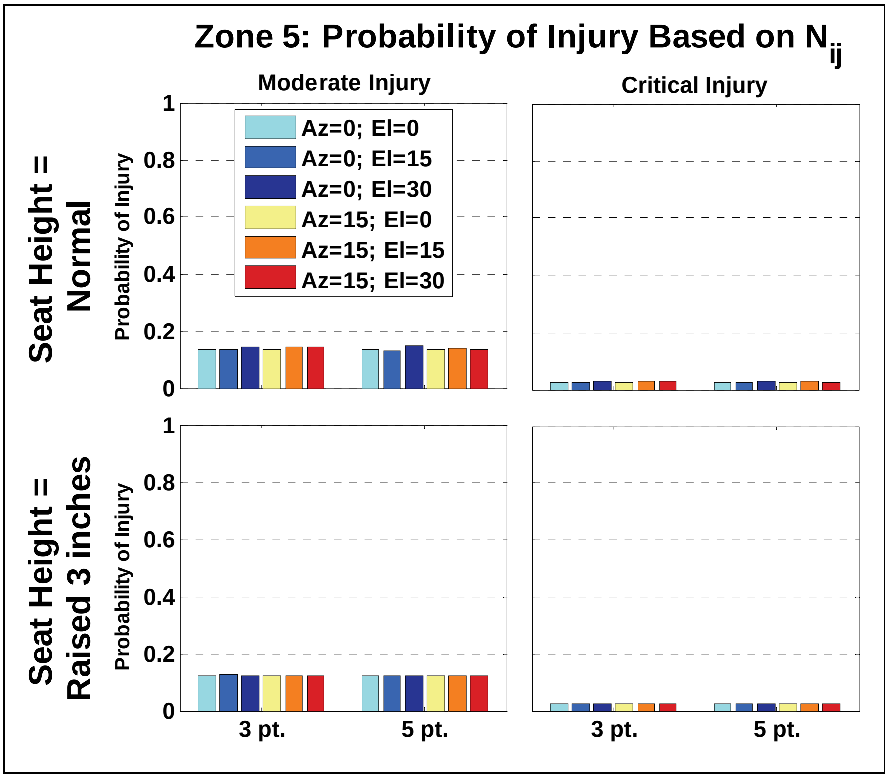

Figure 44. Zone 5 probability of neck injury.

For Zone 4 with the 5-point harness, the probability of a moderate neck injury ranged from 0.129 (12.9%) to 0.132 (13.2%) when the seat height was set to normal and from 0.117 (11.7%) to 0.119 (11.9%) when the seat height was raised 3 inches. Similarly, the probability of a critical neck injury with the 5-point harness was about 0.025 (2.5%) when the seat height was set to normal and ranged between 0.022 (2.2%) to 0.023 (2.3%) when the seat height was raised 3 inches.

For Zone 4 with the 3-point harness, the probability of a moderate neck injury ranged from 0.123 (12.3%) to 0.126 (12.6%) when the seat height was set to normal and from 0.119 (11.9%) to 0.122 (12.2%) when the seat height was raised 3 inches. The probability of a critical neck injury with the 3-point harness was about 0.024 (2.4%) when the seat height was set to normal and was about 0.023 (2.3%) when the seat height was raised 3 inches.

For Zone 5 with the 5-point harness and with the seat set to normal height, the probability of a moderate neck injury varied within the azimuth = 0 condition and between elevation conditions ranging from 0.135 (13.5%) to 0.144 (14.4%). Similarly, the probability of a moderate neck injury varied within the azimuth = 15 condition and between elevation conditions ranging from 0.136 (13.6%) to 0.139 (13.9%). When the seat was raised 3 inches, the probability of a moderate neck injury varied within the azimuth = 0 condition and between elevation conditions ranging from 0.121 (12.1%) to 0.122 (12.2%). Similarly, the probability of a moderate neck injury varied within the azimuth = 15 condition and between elevation conditions ranging from 0.122 (12.2%) to 0.123 (12.3%).

For Zone 5 with the 5-point harness and with the seat set to normal height, the probability of a critical neck injury varied within the azimuth = 0 condition and between elevation conditions ranging from 0.026 (2.6%) to 0.028 (2.8%). Similarly, the probability of a critical neck injury varied within the azimuth = 15 condition and between elevation conditions ranging from 0.026 (2.6%) to 0.027 (2.7%). When the seat was raised 3 inches, the probability of a critical neck injury was consistent within the azimuth = 0 condition and between elevation conditions at about 0.023 (2.3%). Similarly, the probability of a critical neck injury varied within the azimuth = 15 condition and between elevation conditions ranging from 0.023 (2.3%) to 0.024 (2.4%).

For Zone 5 with the 3-point harness and with the seat set to normal height, the probability of a moderate neck injury varied within the azimuth = 0 condition and between elevation conditions ranging from 0.134 (13.4%) to 0.144 (14.4%). Similarly, the probability of a moderate neck injury varied within the azimuth = 15 condition and between elevation conditions ranging from 0.135 (13.5%) to 0.147 (14.7%). When the seat was raised 3 inches, the probability of a moderate neck injury varied within the azimuth = 0 condition and between elevation conditions ranging from 0.123 (12.3%) to 0.125 (12.5%). Similarly, the probability of a moderate neck injury varied within the azimuth = 15 condition and between elevation conditions ranging from 0.121 (12.1%) to 0.122 (12.2%).

For Zone 5 with the 3-point harness and with the seat set to normal height, the probability of a critical neck injury varied within the azimuth = 0 condition and between elevation conditions

ranging from 0.026 (2.6%) to 0.028 (2.8%). Similarly, the probability of a critical neck injury varied within the azimuth = 15 condition and between elevation conditions ranging from 0.026 (2.6%) to 0.029 (2.9%). When the seat was raised 3 inches, the probability of a critical neck injury varied within the azimuth = 0 condition and between elevation conditions ranging from 0.023 (2.3%) to 0.024 (2.4%). The probability of a critical neck injury was fairly consistent within the azimuth = 15 condition and between elevation conditions at about 0.023 (2.3%).

8. Discussion

The objective of this study was to quantify the effect of turret azimuth and elevation, seat height, and occupant restraint type during weapon firing of an NLOS-C on occupant N_{ij}, Hic_{15} and Hic_{36}. Two firing zones were investigated: zone 4 and zone 5.

Although statistically significant differences in Hic_{15} and Hic_{36} were determined between some of the conditions for both the Zone 4 and Zone 5 firing scenarios, the Hic_{15} and Hic_{36} values (and associated injury probabilities) were relatively low. The highest mean Hic_{15} and Hic_{36} values determined for any condition were 15.87 and 12.6, respectively. These are well below the recommended threshold of 700 for Hic_{15} and 1000 for Hic_{36}. The greatest probability of moderate head injury for both Zone 4 and 5 was about 4 in 10,000,000. Although the N_{ij} was much less than the recommended threshold of 1.0 (the greatest N_{ij} value observed in Zone 4 was 0.147; the greatest N_{ij} value observed in Zone 5 was 0.267), the associated neck injury probabilities were greater than the head injury probabilities estimated from the Hic_{15} and Hic_{36} values. Consequently, the discussion focuses on the N_{ij} and the associated probability for injury.

For Zone 4, similar results were found for the conditions of normal seat height and the seat height = raised 3 inches. Statistically significant differences were found between conditions and harness types, and a statistically significant Condition x Harness interaction was determined. For the normal seat height condition, the azimuth = 15, elevation = 15 condition resulted in greater N_{ij} values than both of the other conditions (azimuth = 0, elevation = 30 condition and azimuth = 15, elevation = 0 condition); pairwise comparisons confirmed that these differences were statistically significant. Additionally, the 5-point harness resulted in greater N_{ij} values than the 3-point harness. In contrast, when the seat height was raised 3 inches, the azimuth = 0, elevation = 30 condition resulted in greater N_{ij} values than both of the other conditions (azimuth = 15, elevation = 0 condition and azimuth = 15, elevation = 15 condition); pairwise comparisons confirmed that these differences were statistically significant. In contrast to the normal seat height condition, when the seat height was raised 3 inches, the 3-point harness resulted in greater N_{ij} values than the 5-point harness.

When participants fired to Zone 4, there was a tendency for the probability of injury to be slightly higher with the 5-point harness in the normal seat height condition than in the 3-point harness. In

contrast, in the raised seat height condition, the tendency was the opposite; the probability for a moderate neck injury was slightly higher in the 3-point harness than in the 5-point harness. However, the difference in probability of a moderate neck injury between conditions was very slight; at most, it was 0.005 (0.5%), and these differences may not be operationally relevant. This trend was less apparent when the probability of a critical neck injury is investigated.

It is important to note that across conditions, harness types, and seat heights, the probability of a moderate neck injury when participants fired to Zone 4 ranged between 0.117 and 0.132 (figure 45). These probabilities indicate that on average, a moderate neck injury could be expected 11.7% and 13.2% of the time the weapon is fired to Zone 4. These results could be interpreted to indicate that one in every eight firings of the NLOS-C to Zone 4 will result in a moderate neck injury. The corresponding probability of a critical neck injury for Zone 4 ranged from 0.023 to 0.025, indicating that a critical neck injury would be expected 2.3% to 2.5% of the time the weapon is fired to Zone 4. These results could be interpreted to indicate that 1 in every 43 firings of the NLOS-C to Zone 4 will result in a critical neck injury.

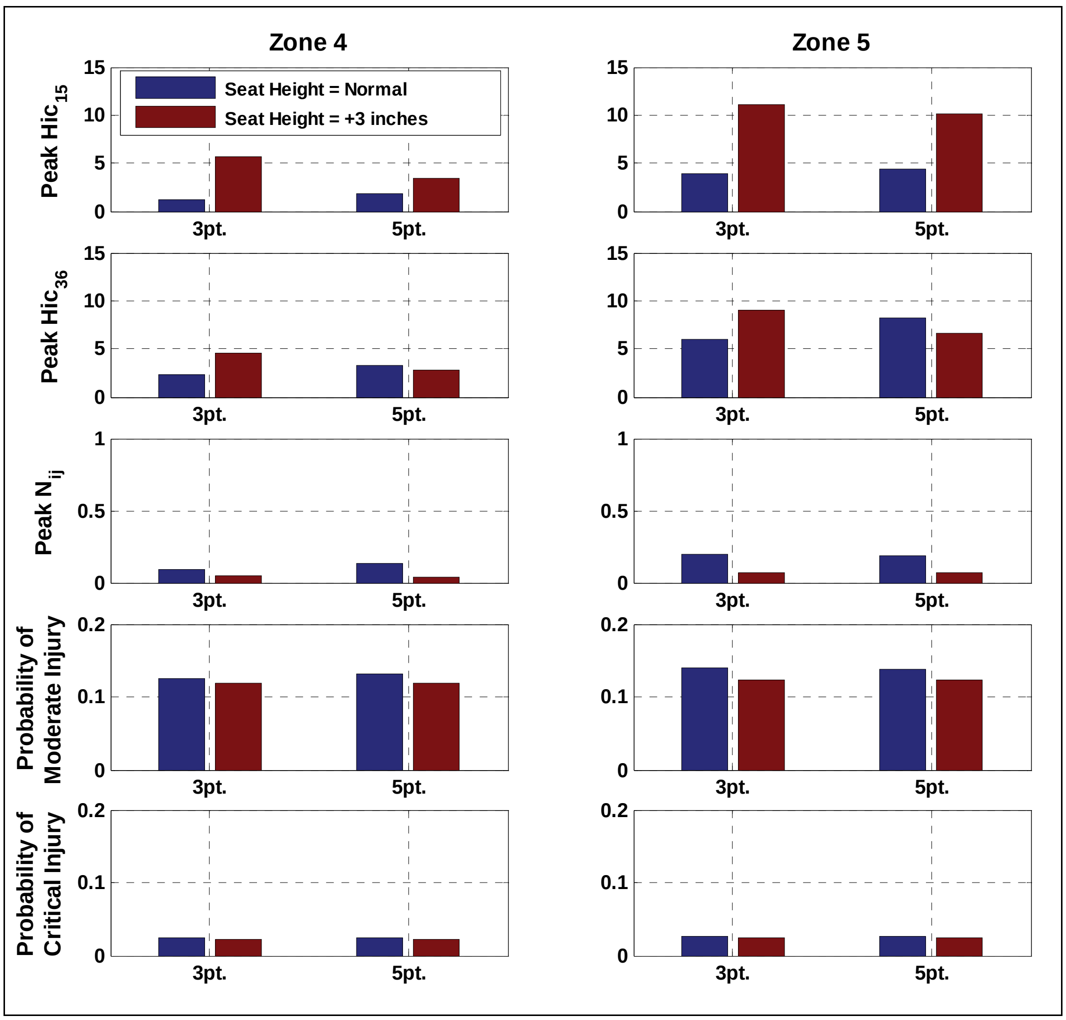

Figure 45. Summary of results across all conditions.

For Zone 5, with the seat height set to normal, statistically significant differences were determined between elevation conditions, and a statistically significant Azimuth x Elevation interaction was determined. The 30-degrees-of-elevation condition resulted in greater N_{ij} values than both the 0-degrees-of-elevation condition and the 15-degrees-of-elevation condition. Pairwise comparisons confirmed that these differences were statistically significant. When the seat height was raised 3 inches, statistically significant differences were found between azimuth conditions, elevation conditions, and harness conditions. Greater N_{ij} values were found in the condition of azimuth = 0 degrees than in the condition of azimuth = 15 degrees. Similarly, greater N_{ij} values were found with the 3-point harness than with the 5-point harness. The elevation = 15 degrees resulted in greater N_{ij} values than both the conditions of elevation = 0 degrees and the elevation = 30. Pairwise comparisons confirmed that statistically significant differences between the condition of elevation = 15 degrees and both the conditions of elevation = 0 and the elevation = 30, but no statistically significant differences were found between condition of elevation = 0 and the elevation = 30. As with Zone 4, even though there were statistically significant differences between conditions, the differences were so small that there likely is not an operational difference between conditions. However, the probability of neck injury associated with the observed values of N_{ij} is important.

Across all the elevation, azimuth, harness type, and seat height conditions, the probability of a moderate neck injury ranged from 0.121 to 0.147. These probabilities correspond to a 12.1% and 14.7% chance of injury when the weapon is fired to Zone 5. These results could be interpreted to indicate that one in every seven to eight firings of the NLOS-C to Zone 5 will result in a moderate neck injury. The probability of a critical neck injury for Zone 5 ranged from 0.023 to 0.029 across conditions for firing to Zone 5. This corresponds to a 2.3% to 2.5% chance of a critical neck injury when the weapon is fired. These results could be interpreted to indicate that 1 in every 43 firings of the NLOS-C to Zone 5 will result in a critical neck injury.

It is also important to note that the NHTSA guideline is based on a single impulse event (such as a car striking a tree) and does not take into account the cumulative effects of multiple impulses (such as the repeated firing of the NLOS-C), which indicates that the actual injury rate may be greater than the predicted injury rate presented in this report. At the time this report was written, injury standards for multiple impulse events had not been established.

9. Concluding Remarks

The goal of this study was to quantify the effects of turret azimuth and elevation, seat height, and harness type on the forces, torques, and accelerations experienced by the NLOS-C occupant during weapon firing. Based on the standards used by NHTSA, the acceleration of the head and the forces and torques experienced by the neck of the occupant of an NLOS-C during weapon firing

are less than the injury criteria for the 50th percentile male. Resulting probability of injury rates were nearly zero for head injuries but were as high as about 0.147 (14.7%) for moderate neck injuries. The estimated probability of neck injury does not account for possible cumulative effects of the repeated impulses of the weapon firing. It is important to note that the injury criteria and probability for injury calculations were developed for single impulse events (such as a car accident) and may not be appropriate for multiple impulse events (such as the repeated firing of the weapon). Because of this and the fact that there may be a cumulative effect of repeated impulses on the probability of injury, the injury probabilities reported may be artificially low. At the time this report was written, injury standards for multiple impulse events had not been established.

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